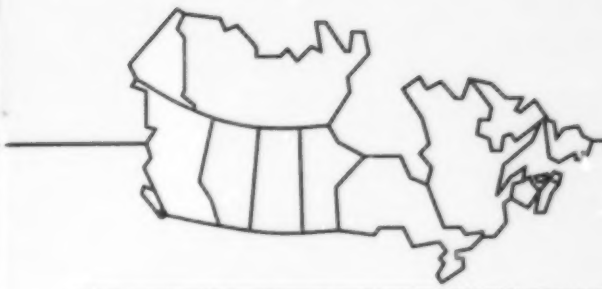
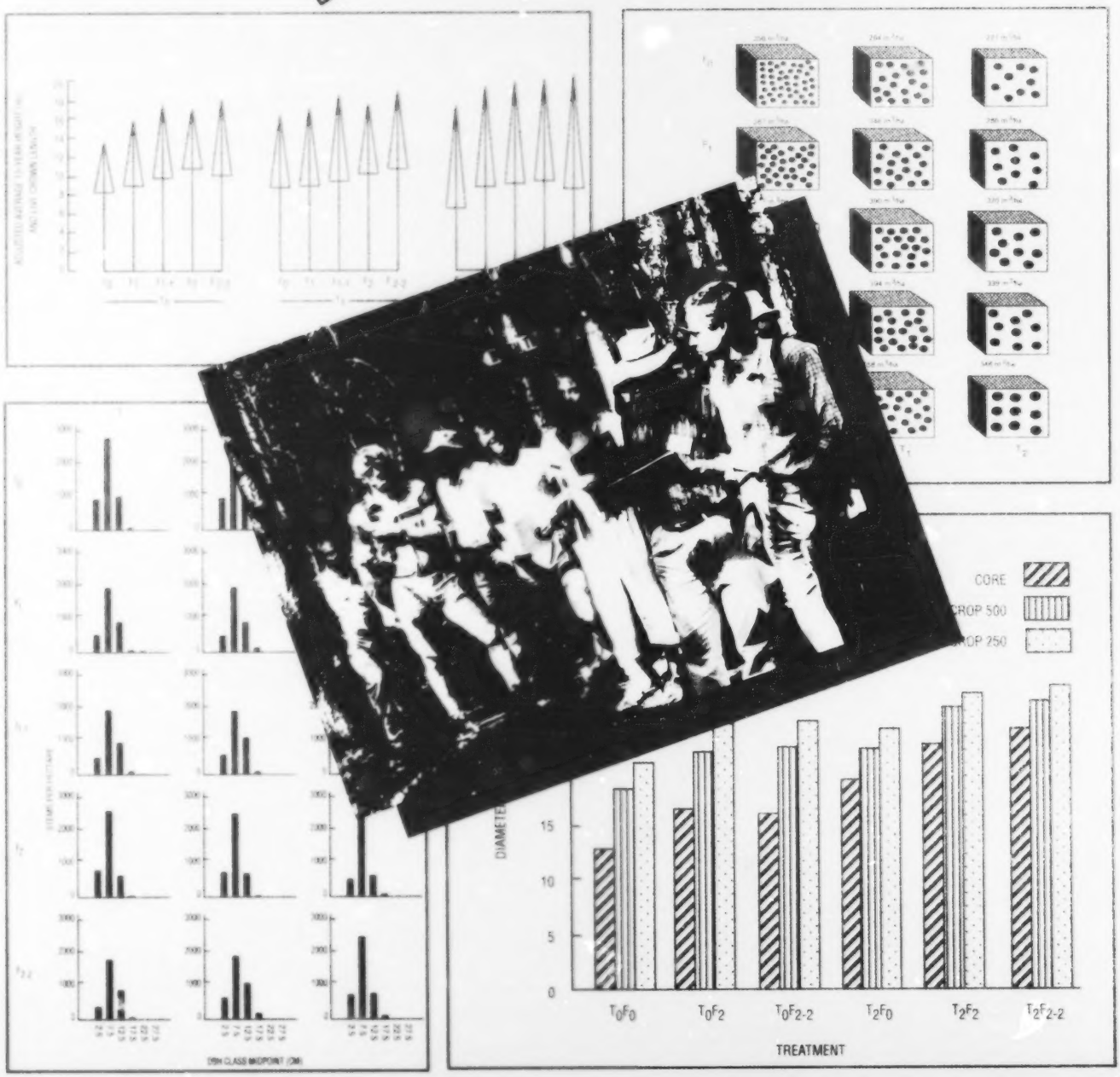
Forestry Canada Forêts Canada

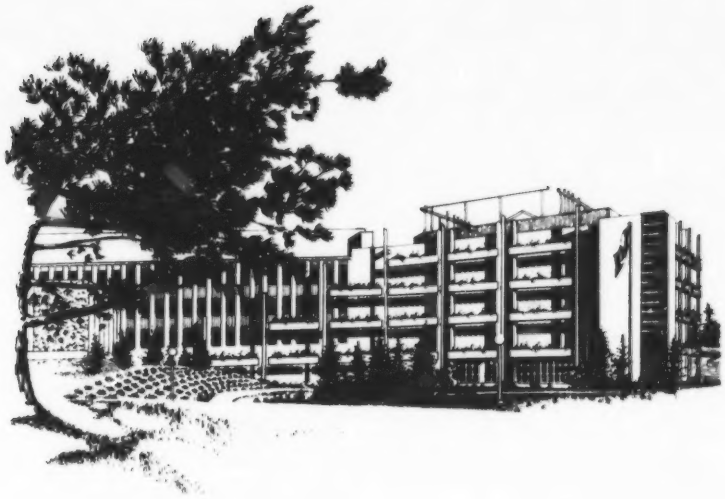
Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 15-year growth response

E. R. Gardner

Information Report BC-X-319
Pacific and Yukon Region







The Pacific Forestry Centre is one of six regional and two national establishments of Forestry Canada. Situated in Victoria with a district office in Prince George, The Pacific Forestry Centre cooperates with other agencies, the forest industry, and educational institutions to promote the wise management of the forest resources of British Columbia and the Yukon.

The Pacific Forestry Centre undertakes research in response to the needs of the various managers of the forest resource. The results of this research are distributed in the form of scientific and technical reports and other publications.

About the Author

Eleanor Gardner

Eleanor Gardner joined the Pacific Forestry Centre in 1985 after completing a B.Sc.F. at the University of British Columbia in 1984. She is presently completing her M.Sc. at the University of Minnesota in Minneapolis/St. Paul. Her current research is focussed on the evaluation of several methods for measuring fertilizer response.

Cover: The photograph on the front cover is from one of many technology transfer tours occuring annually at the Shawnigan Lake research site.

Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 15-year growth response

by

E.R. Gardner

Forestry Canada
Pacific and Yukon Region
Pacific Forestry Centre

BC-X-319

1990

90-05789/

Forestry Canada
Pacific and Yukon Region
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia
V8Z 1M5
Phone (604)388-0600

© Minister of Supply and Services Canada, 1990
ISSN 0830-0453
ISBN 0-622-17647-2
Cat. No. Fo46-17/319E
Printed in Canada

Additional copies of this publication
are available in limited quantities
at no charge from the Pacific Forestry Centre

Microfiches of this publication may be purchased from:

MicroMedia Inc.
Place du Portage
165, Hotêl-de-Ville
Hull, Quebec
J3X 3X2

Contents

Abstract vii
Résumé viii
Acknowledgments ix
1. Introduction 1
2. Documentation of the database 1
2.1 Terminology 1
2.2 Variables measured 2
2.3 Variables estimated 2
2.3.1 Total volume 2
2.3.2 Merchantable volume 3
3. Methods of data analysis 3
3.1 Land area basis 4
3.2 Average individual tree size 4
3.3 Growth of trees of similar initial size 4
3.4 Crop tree analysis 4
4. Results 6
4.1 Mortality 6
4.2 Diameter 6
4.2.1 Quadratic mean diameter 6
4.2.2 Periodic annual diameter increment 12
4.2.3 Diameter growth response of trees of similar initial size 12
4.2.4 Diameter distribution 14
4.2.5 Crop tree response 14
4.3 Total basal area 14
4.4 Height 16
4.4.1 Average height 18
4.4.2 Periodic annual height growth 18
4.4.3 Top height Growth 18
4.4.4 Height distribution 20
4.5 Live crown length 20
4.6 Volume 20
4.6.1 Total volume and volume increments per hectare 20
4.6.2 Average individual stem volume 24
4.6.3 Crop tree response 24
4.6.4 Merchantable volume 24
12.5 cm diameter limit 24
17.5 cm diameter limit 28
5. Discussion 32
5.1 Influence of initial stand conditions 32
5.2 Thinning 33
5.3 Fertilization 33
5.4 Refertilization 33
5.5 Thinning vs fertilization 34
6. Conclusions 34
Literature cited 35
Appendices 37

Tables

1 Levels of thinning and fertilization 1

2 List of variables measured for the core, volume, and extra height trees 2

3 Number of live stems per hectare by treatment and year 7

4 Numbers and quadratic mean diameter of trees that died 7

5 Causes of mortality to year 15 10

6 (a) Quadratic mean diameter by treatment and year 11
(b) Periodic annual diameter increments for each treatment combination 11

7 (a) Basal area per hectare by treatment and year 17
(b) Net periodic annual basal area increments for each treatment combination 17

8 (a) Average heights by treatment and year 19
(b) Periodic annual height increments for each treatment combination 19

9 Ranges of heights 15 years after treatment (based on volume and extra height trees) 20

10 Average percent live crown and live crown length by treatment and year 21

11 (a) Total volume per hectare by treatment and year 22
(b) Net periodic annual volume increment for each treatment combination 22

12 (a) Merchantable volume per hectare by treatment and year based on a dbh limit of 12.5 cm 29
(b) Net periodic annual merchantable volume increments for each treatment combination based on dbh limit of 12.5 cm 29

13 (a) Merchantable volume per hectare by treatment and year based on a dbh limit of 17.5 cm 30
(b) Net periodic annual merchantable volume increments for each treatment combination based on a dbh limit of 17.5 cm 30

Figures

1 Diameter distributions among 5-cm dbh classes in plots prior to treatment. 5

2 The effects of thinning and urea fertilization 15 years after treatment. 8

3 Factors influencing quadratic mean diameter. 10

4 Adjusted quadratic mean diameter for each treatment combination 15 years after initial treatment....12

5 Average annual diameter increment for each treatment combination between years 0 and 15 by 5-cm dbh classes 13

6 Diameter distribution for each treatment combination by 5-cm dbh class 15 years after initial treatment....15

7 Adjusted quadratic mean diameter of the core and crop trees for the six extreme treatments 15 years after initial treatment. 16

8 Adjusted average heights and average live crown lengths for each treatment combination 15 years after initial treatment....18

9 Average annual height increments of the top height trees during the first 9 years after initial treatment. 21

10 Adjusted total volume per hectare for each treatment combination 15 years after initial treatment. 23

11 Adjusted total volume per hectare, quadratic mean diameter, and stems per hectare for each treatment combination 15 years after initial treatment. 25

12 Average annual stem volume increments between year 0 and year 15 by initial 5-cm dbh classes for each treatment combination. 26

13 Adjusted total volume per hectare of the crop trees 15 years after initial treatment for each treatment combination. 27

14 Adjusted total stand volume of core and crop trees for the six extreme treatments 15 years after initial treatment....28

15 Adjusted merchantable volume per hectare 15 years after initial treatment for each treatment combination. 31

Appendix Tables

A1 Volume equation coefficients by treatment for individual tree volumes 12 years after treatment 37

A2 Volume equation coefficients by treatment for individual tree volumes 15 years after treatment 38

A3 Analysis of covariance on quadratic mean diameters 15 years after treatment 38

A4 Analysis of covariance on diameters of 250 crop trees per hectare 15 years after treatment 39

A5 Analysis of covariance on diameters of 500 crop trees per hectare 15 years after treatment 39

A6 Analysis of covariance on total basal area 15 years after treatment 39

A7 Analysis of covariance on average heights 15 years after treatment 39

A8 Analysis of variance on annual height increments of the top height trees for the first nine years after treatment 40

A9 Analysis of variance on annual height increments of the top height trees from year 3 to year 9 40

A10 Analysis of covariance on total volume 15 years after treatment 40

A11 Analysis of covariance on individual tree volumes 15 years after treatment 40

A12 Analysis of covariance on total volume of 250 crop trees per hectare 15 years after treatment 41

A13 Analysis of covariance on total volume of 500 crop trees per hectare 15 years after treatment 41

A14 Analysis of covariance on merchantable volume with a dbh limit of 12.5 cm 15 years after treatment 41

A15 Analysis of covariance on merchantable volume with a dbh limit of 17.5 cm 15 years after treatment 42

A16 Adjusted means from analyses of covariance 15 years after treatment 42

Abstract

This report documents the 15-year growth response of a Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) stand to thinning and urea fertilization. The initial treatments were carried out when the stand was 24 years old. Growth responses were analyzed on a per hectare, individual tree, crop tree, and tree size class basis.

Most mortality occurred in the unthinned plots, and within these plots fertilization has accelerated mortality. In the unthinned and fertilized plots, up to 30% of the trees died, and most of these were small suppressed trees.

Fifteen years after initial treatment, the unthinned plots had the most total volume followed by the moderately thinned and then the heavily thinned plots. However, in terms of total merchantable volume at a dbh limit of 17.5 cm, the order was reversed. In all thinning levels, fertilization increased the total and merchantable volumes and the application of 448 kg N/ha resulted in significantly more volume than 224 kg N/ha.

Average individual tree size, measured by dbh or stem volume, was increased by both thinning and fertilization and the response to fertilization was greatest in the heavily thinned plots. Thinning alone increased the quadratic mean diameter more than fertilization alone, but both treatments caused similar increases in the average diameter of the largest 250 and 500 trees per hectare.

The largest trees in all plots continued to grow fastest, but the smallest trees benefited most from the treatments in terms of increased relative growth rates. For example, in the heavily thinned plots fertilized twice with 448 kg N/ha, the trees initially in the 5-10 cm diameter class added stem volume six times faster than trees of similar size in the control plots.

For the period 12 to 15 years after treatment, all plots fertilized once with either 224 or 448 kg N/ha had net annual volume increments greater than unfertilized plots with the same level of thinning. These increases in volume growth rates were largest in the heavily thinned plots followed by the moderately thinned and then the unthinned plots.

The volume response to a second fertilizer treatment, applied 9 years after the first, was greatest in the heavily thinned plots. In these plots a volume response to the second application of fertilizer was still evident in the period 12 to 15 years after initial treatment. However, in the unthinned plots, the volume response to a second application of fertilizer was limited to the first 3 to 4 years after application. In the period from year 12 to year 15, net annual volume increments of the unthinned refertilized plots fell below those measured in the 3-year period prior to refertilization. In all thinning levels, there have been no measurable differences between the response to one application of 448 kg N/ha and that to two applications of 224 kg N/ha.

With the first 3 years after treatment excluded so that the observed effect of thinning shock is removed, annual top height growth in the period from 3 to 9 years after initial treatment was significantly increased by both fertilization and thinning.

Résumé

Dans le présent article, on étudie la réaction de croissance, sur une période de 15 ans, d'un peuplement de sapins de Douglas (Pseudotsuga menziesii (Mirb) Franco) à l'éclaircie et à la fertilisation à l'urée. Les premiers traitements ont été réalisés lorsque le peuplement était âgé de 24 ans. Les réactions de croissance ont été analysées par hectare, par arbre, par arbre du peuplement final et par classe de dimension.

Le taux de mortalité le plus élevé a été observé dans les parcelles non éclaircies et, à l'intérieur de ces parcelles, la fertilisation a accéléré la mortalité. Dans les parcelles non éclaircies et fertilisées, jusqu'à 30 % des arbres sont morts et la plupart de ces derniers étaient de petits arbres opprimés. Quinze ans après le traitement initial, ce sont les parcelles non éclaircies qui présentaient le volume total le plus important, suivies des parcelles modérément éclaircies et des parcelles très éclaircies. Cependant, en ce qui concerne le volume marchand total au dbh limite de 17,5 cm, l'ordre était inversé. Pour tous les degrés d'éclaircie, la fertilisation a augmenté les volumes total et marchand, et l'application de 448 kg N/ha a entraîné une augmentation de volume plus importante que l'application de 224 kg N/ha.

La grosseur moyenne des arbres, en termes de dbh ou de volume de la tige, a été augmentée par l'éclaircie et la fertilisation, et la réaction à la fertilisation a été supérieure dans les parcelles très éclaircies. L'éclaircie seule a entraîné une plus forte augmentation du diamètre de la tige de surface terrière moyenne que la fertilisation seule, mais les deux traitements ont entraîné des augmentations semblables du diamètre moyen des 250 et 500 arbres les plus gros par hectare.

Dans toutes les parcelles, les plus gros arbres ont continué à croître plus rapidement que les autres, mais ce sont les plus petits arbres qui ont le plus bénéficié des traitements, en termes d'augmentation du taux de croissance relatif. Par example, dans les parcelles très éclaircies fertilisées deux fois avec 448 kg N/ha, le volume de la tige des arbres qui se trouvaient initialement dans la classe de diamètre de 5 à 10 cm a augmenté six fois plus vite que celui des arbres de taille semblable dans les parcelles témoins.

Pour la période de 12 à 15 ans qui a suivi la traitement, toutes les parcelles fertilisées une fois avec 224 ou 448 kg N/ha ont connu une augmentation annuelle nette de volume supérieure à celle des parcelles non fertilisées qui ont subi le même degré d'éclaircie. Les parcelles très éclaircies ont subi les plus fortes augmentations de volume, suivies des parcelles modérément éclaircies et des parcelles non éclaircies.

L'augmentation du volume par suite d'une deuxième application d'engrais, neuf ans après la première, a été supérieure dans les parcelles très éclaircies. Dans ces parcelles, la modification du volume par suite de la deuxième application d'engrais était toujours évidente durant la période située entre 12 et 15 ans après le premier traitement. Cependant, dans les parcelles non éclaircies, l'effet sur le volume d'une deuxième application d'engrais s'est limité aux trois à quatre années qui ont suivi l'application. Durant la période allant de la douxième à la quinzième année, les augmentations nettes du volume annuel dans les parcelles non éclaircies refertilisées ont été inférieures aux augmentations mesurées durant la période de trois ans qui a précédé la refertilisation. Pour tous les degrés d'éclaircie, on n'a observé aucune différence mesurable entre la réponse à une seule application de 448 kg N/ha et la réponse à deux applications de 224 kg N/ha.

Si l'on exclut les trois premières années qui ont suivi le traitement, de façon à éliminer l'effet obervé du choc causé par l'éclaircie, la croissance annuelle de la hauteur des arbres dominants durant la période allant de trois à neuf ans après le traitement initial a augmenté de façon importante par suite de la fertilisation et de l'éclaircie.

Acknowledgments

The contributions of the following individuals are gratefully acknowledged: René de Jong for his help with manuscript revisions; Chuck Layton for the data collection; the other members of the Shawnigan Lake Project (Holger Brix, Al Mitchell, Doug Pollard, Tony Trofymow, Hugh Barclay, Valin Marshall and Caroline Preston) for their continued support and encouragement and for reviewing the manuscript; and Mike Bonnor, Jim Arnott, and Steven Omule for their detailed review of the manuscript.

1.0 Introduction

The Shawnigan Lake project was established in 1970 with the objective of determining the mechanisms of response to thinning and nitrogen fertilization within a Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) ecosystem. The mensurational aspects presented here provide a baseline of information for the other integrated studies on tree physiology, water relations, nitrogen cycling, soil chemistry and the role of soil flora and fauna.

The study site is located within the very dry maritime Coastal Western Hemlock biogeoclimatic subzone (CWHxm)[1] and consists of very dry, nutrient-poor to medium ecotopes (Klinka et al. 1984). The Douglas-fir site index is 25 m at breast height age 50 based on Bruce's site index equations (Bruce 1981).

The experimental design has been described in detail by Crown and Brett (1975) and Crown et al. (1977). The main experiment was originally laid out as a 3x3 factorial in a completely randomized design. Each square plot is 0.0405 ha in area, surrounded on all sides by a 15-m-wide treated buffer strip. There were three levels of thinning and three levels of nitrogen fertilization, resulting in nine initial treatment combinations. Each treatment combination was replicated twice in two successive years, 1971 and 1972, for a total of 36 plots. In 1981, 9 years after the first application of fertilizer, the plots that were initially fertilized in 1972 were refertilized at their original rates, resulting in a total of 15 treatment combinations. The levels of thinning and fertilization are listed in Table 1.

Thinning was conducted so as to obtain an even spacing of residual trees together with a maximum number of crop trees while maintaining representation across a range of diameter classes. The fertilizer applied was forest grade urea.

Results presented in this report summarize the 15-year growth response in the main experiment. Previous publications (Crown et al. 1977; Hall et al. 1980; Barclay et al. 1982; Barclay and Brix 1985a) reported results after 3, 6, 9, and 12 years, respectively. This report includes several new features: the recalculation of all merchantable volumes of Douglas-fir; the presentation of merchantable volumes to diameter limits of 12.5 and 17.5 cm; and the inclusion of measurements of the minor tree species present within the unthinned plots. Minor species include western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* Donn), western white pine (*Pinus monticola* Dougl.), lodgepole pine (*Pinus contorta* var. *contorta* Dougl.), and grand fir (*Abies grandis* (Dougl.) Lindl.). Fifteen years after initial treatment, they accounted for 0.8 % of the total volume and 1.8 % of the stems in the unthinned plots. In the thinned plots, minor species were cut at the time of thinning.

In addition to the main experiment, there are subsidiary experiments at the Shawnigan Lake site including plots fertilized with ammonium nitrate, with higher rates of urea, and with combinations of urea, phosphorous, and sulpher. Results from the ammonium nitrate and high rates of urea experiments have been reported separately (Barclay and Brix 1984; Barclay and Brix 1985b). No results have yet been published from the plots fertilized with combinations of urea, phosphorous, and sulpher.

Table 1. Levels of thinning and fertilization

Thinning	
Symbol	Treatment
T_0	No thinning
T_1	Approximately 1/3 basal area removed
T_2	Approximately 2/3 basal area removed

Fertilization	
Symbol	Treatment
F_0	No fertilization
F_1	224 kg N/ha
F_{1-1}	224 kg N/ha applied twice
F_2	448 kg N/ha
F_{2-2}	448 kh N/ha applied twice

2.0 Documentation of the database

2.1 Terminology

There are three types of trees sampled within each plot: core, volume, and extra height trees. The core trees are those located within the central 0.0405-ha core plots. The volume trees are a subsample of the core trees on which more frequent and detailed measurements are taken to allow for accurate volume estimates across a range of diameters. Originally there were 464 volume trees, but mortality (primarily due to suppression) has reduced this number to 394. The extra height trees are a separate subsample of the core trees; these were

1. Formally the CDFb subzone. This new terminology represents the recent work of the British Columbia Forest Service ecological correlation program.

randomly chosen within specified diameter classes to ensure that height measurements are taken over the full range of diameter classes. These trees were selected 12 years after treatment when it was decided that a larger sample of height measurements was required. All volume and extra height trees are Douglas-fir.

2.2 Variables measured

The variables measured for the core, volume and extra height trees are listed in Table 2.

2.3 Variables estimated

2.3.1 Total volume

Total volume estimates (entire tree stem, outside bark, including stump and top) are based on the volume tree data, where Newton's formula (Husch et al. 1982) is applied to the taper measurements of each volume tree to calculate segment volumes between taper steps.

In previous reports, the total volume of Douglas-fir (outside bark) 0, 3, 6, 9 and 12 years after initial treatment was estimated using equations of the form

$$\log(VOL) = a + b\cdot\log(DBH) + c\cdot\log(HT)$$

where VOL = Total volume (m^3/tree)
DBH = Diameter (cm) at breast height (1.3 m)
HT = Total tree height (m)
a,b,c = regression coefficients

In calculating these volume estimates, total tree heights were based on actual measurements in years 3, 6, and 9 and were estimated from volume tree data at year 12.

Table 2. List of variables measured for the core, volume, and extra height trees.

DBH = Diameter at breast height (1.30m)
HT = Total tree height
HTLC = Height to live crown
TAPER = Taper measurements, positioned on the stem at 2.54-cm diameter decrements at the time of treatment

YEARS SINCE TREATMENT	CORE TREES			VOLUME TREES				EXTRA HEIGHT TREES		
	DBH	HT	HTLC	DBH	HT	HTLC	TAPER	DBH	HT	HTLC
0	•	•	•	•	•	•	•	•	•	•
1	•			•	•			•		
2	•			•	•			•		
3	•	•		•	•		•	•	•	
4				•	•					
5				•	•					
6	•	•	•	•	•	•	•	•	•	•
7				•	•					
8				•	•					
9	•	•	•	•	•	•	•	•	•	•
10				•	•					
11				•	•					
12	•			•	•	•	•	•		
13				•	•				•	
14				•	•				•	
15	•			•	•	•	•	•	•	•

In this report, total volumes 12 and 15 years after initial treatment have been calculated using equations of the form:

$$VOLINC = a + b \cdot (BA) + c \cdot (BAINC)$$

where VOLINC = total volume increment from year 9 to year 12 or from year 9 to year 15 (m^3)
BA = basal area of the tree at year 9 (m^2)
BAINC = basal area increment from year 9 to year 12 or from year 9 to year 15 (m^2)
a,b,c = regression coefficients

Since heights were no longer measured on all trees after year 9, this form of equation was chosen over that used previously since it does not include height as an independent variable. In addition, there is a very strong relationship between basal area and volume growth. Individual equations were calculated for each of the nine treatments, in each of the two establishment years, for volumes at year 12 and year 15, for a total of 36 equations (Appendix Tables A1 and A2).

Total volumes of minor species were calculated using the British Columbia Forest Service volume equations (1976).

2.3.2 Merchantable volume

Merchantable volume is defined in this report as the total volume inside bark between a stump that is 30 cm high and a top that has a diameter of 10 cm inside bark. No reductions are made for decay, waste, and breakage.

In all previous reports, merchantable volume of Douglas-fir was determined using close utilization factors developed by Browne (1962). Merchantable volume of the minor species was not included.

In this report, merchantable volumes of Douglas-fir for years 0 through 15 have been recalculated using the new merchantable volume equations for small coastal Douglas-fir (Omule et al. 1987). Merchantable volumes of minor species have been calculated using the British Columbia Forest Service (1976) merchantable volume factors.

In the system developed by Omule et al. (1987) to calculate merchantable volume of a tree, the total volume inside bark is first estimated from its total height and diameter, and then is multiplied by a merchantable volume factor based on the tree's diameter. As heights of all core trees were only measured until year 9, it was not feasible to use Omule et al.'s equation to predict the total volume inside bark on all trees for years 0 through 15. Instead, the data used by Omule et al. (1987) were used here to develop the following equations:

$$\ln(VIB + 1) = -0.00100567 + 0.85420712 \cdot \ln(VOB + 1)$$

where VIB = total volume inside bark
VOB = total volume outside bark
R^2 = 0.99
SEE = 0.016 (logarithmic standard error)
n = 2181 trees (9.7 to 45 cm dbh)

All trees with a dbh less than 9.7 cm were discarded from the data set prior to the development of the equation, because with a minimum 10 cm inside bark top diameter limit, these trees have no merchantable volume. This single equation was used for all trees for years 0 through 15. In using this equation, the assumption is made that a tree of a given volume outside bark will have the same volume inside bark, regardless of treatment (i.e., bark thickness is not affected by treatment). This equation has been corrected for logarithmic bias (see, e.g., Miller 1984).

3.0 Methods of data analysis

All statistical analyses were conducted using the statistical analysis software SAS as implemented on the Pacific Forestry Centre's VAX 8650. All tests for significance used a $P \leq 0.05$. All analyses of variance and covariance used the general linear model procedure (SAS Institute Inc. 1985, page 433). When there was not a significant treatment interaction, the means of main effects were compared (SAS Contrast statement). Individual adjusted treatment means were compared using pairwise t tests (SAS Lsmeans statement)[2].

Throughout this report, adjusted means and totals are presented when one or more covariates were found to be significant. By adjusting treatment means and totals to remove pretreatment differences, lower experimental errors and more precise comparisons among treatments can be obtained (Snedecor and Cochran 1967, page 420).

2. Other mean separation techniques (e.g., Duncan's) cannot be readily applied to adjusted treatment means because they are not independent (Freund et al. 1986, page 146).

3.1 Land area basis

Analyses of covariance were performed on total volume, merchantable volume, and basal area per hectare 15 years after treatment. In each case, plot totals were compared using plot pretreatment values as covariates. For each analysis, the following covariates were used:

Analysis	Covariate (pretreatment measurements)
1. VOL/ha	: VOL/ha
2. MVOL/ha (12.5 cm)	: Average BA/tree
3. MVOL/ha (17.5 cm)	: MVOL/ha and Average BA/tree
4. BA/ha	: Total BA/ha * Average BA/tree

where VOL = Total volume
MVOL= Total merchantable volume
BA = Total basal area

Although analysis of covariance can be used to adjust for initial differences in total volume or total basal area, it will not fully account for initial differences in stand structure. Figure 1 shows the pretreatment diameter distributions for the various treatment plots. Initial average diameters ranged from 7.4 to 8.8 cm, and the initial number of stems per hectare ranged from 3226 to 4852.

3.2 Average individual tree size

Analyses of covariance were performed on quadratic mean diameter (diameter of the tree of mean basal area), height, and individual stem volume at 15 years. Plot averages, rather than individual tree measurements, were used in these analyses, with corresponding pretreatment plot averages as covariates[3]. For each analysis, the following covariates were used:

Analysis	Covariate (pretreatment measurements)
1. DBHq	: Average plot DBHq
2. Average Height	: Average plot Height
3. Top Height Growth	: None
4. Individual Tree Volume	Average Individual Tree Volume

where DBHq = quadratic mean diameter (diameter of a tree of mean basal area)

3.3 Growth of trees of similar initial size

The growth response of trees of similar pretreatment size was examined by grouping trees into similar diameter classes at the time of treatment, and comparing the periodic annual increments to year 15 within each class. This procedure was carried out for both diameter and individual stem volume in each of the diameter classes common to all treatments.

3.4 Crop tree analysis

In crop tree analysis, a specified number of surviving trees with the largest diameters at the time of treatment were chosen from each plot. In previous reports, the largest 8 and 25 trees per plot were chosen to approximate the largest 200 and 600 stems per hectare, respectively. In this report, the largest 10 and 20 trees per plot were chosen to approximate the largest 250 and 500 stems per hectare. These numbers were chosen because 250 stems per hectare is currently regarded as a minimum to be left after a commercial thinning, and 500 stems per hectare is a common number of stems to be left after a juvenile spacing when no subsequent commercial thinning is planned (British Columbia Forest Service 1989). Analyses of covariance were performed on quadratic mean diameter and total volume for both the 250 and 500 crop trees. For each analysis, the following covariates were used:

Analysis	Covariate (pretreatment measurements)
1. DBHq	: DBHq
2. VOL/ha	: VOL/ha

where DBHq = quadratic mean diameter
VOL = total volume of crop trees

3. The use of individual tree size prior to thinning as a covariate would have meant that only trees remaining after thinning could be used in the analysis. This would have eliminated the true measure of average tree size in the plot prior to thinning, as thinned trees would have been excluded from the analysis.

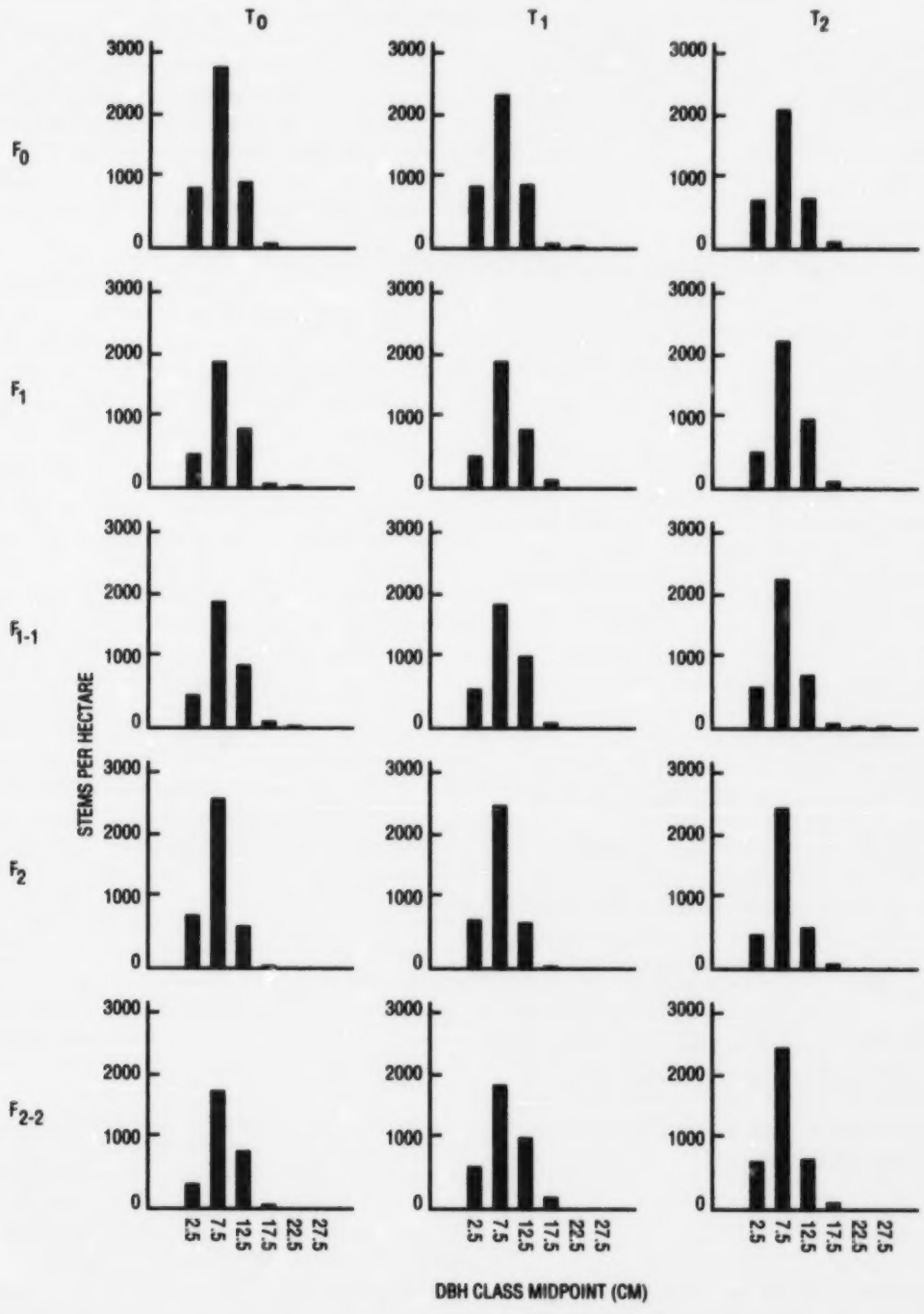


Figure 1. Diameter distributions among 5-cm dbh classes in plots prior to treatment.

4.0 Results

The photographs in Figure 2 show the T_0F_0, T_0F2, $T2F_0$, and T2F2 plots 15 years after treatment and illustrate the differences in average tree size and stand structure.

4.1 Mortality

Mortality summaries provide an indication of how stand structure within the various treatments changes over time. This information in turn helps in the interpretation of the other measures of stand development.

Most mortality to year 15 occurred in the unthinned plots, and within these plots fertilization accelerated mortality (Tables 3 and 4). Suppression was the greatest cause of mortality in the unthinned plots: 10% of the stems in the T_0F_0 plots, 15% in the T_0F_1 plots, 30% in the $T_0F_{1\text{-}1}$ plots, 29% in the T_0F_2 plots, and 25% in the $T_0F_{2\text{-}2}$ plots died due to suppression (Table 5). Snow damage caused some scattered mortality, and white pine blister rust (*Cronartium ribicola* J.C. Fisch) killed most of the few white pine remaining in the unthinned plots. White pine originally in the T_1 and T_2 plots were thinned out.

Fewer trees died as a result of suppression in the moderately thinned plots, but, as in the unthinned plots, fertilization accelerated mortality due to suppression. To year 15, 12% of the stems in the $T_1F_{2\text{-}2}$ plots died due to suppression whereas less than 1% died due to suppression in the T_1F_0 plots. Scattered snow damage also caused mortality in the T_1 plots, and in one of the T_1F_0 plots three trees were killed by root rot (*Phellinus weirii* (Murr.) Gilbertson).

To year 15, no trees have yet died in the heavily thinned plots as a result of suppression. Thinning removed many trees which would have died, and allowed others to survive which would otherwise have died. Mortality in these plots was less than 3%, and was all due to snow damage.

4.2 Diameter

Diameter growth response was assessed by comparing quadratic mean diameters at year 15, and comparing periodic annual diameter increment between year 0 and year 15. Differences in quadratic mean diameter are the result of growth differences between treatments, an immediate arithmetic increase brought about by thinning (removal of smaller trees), and subsequent arithmetic increases due to mortality of smaller trees in the unthinned plots (Figure 3). Periodic annual increment, however, is a measure of the growth of surviving trees over a specified period, and therefore does not include any arithmetic increases.

4.2.1 Quadratic mean diameter

Quadratic mean diameter for each treatment and year is presented in Table 6a. An analysis of covariance on quadratic mean diameter at year 15 showed a significant interaction between thinning and fertilization (Appendix Table A3). While increased thinning intensity resulted in larger quadratic mean diameter, the response to the different levels of fertilizer varied among thinning levels. The adjusted quadratic mean diameter at year 15 for each treatment combination is shown in Figure 4, and is listed in Appendix Table A16.

Fertilization increases diameter in two ways: 1) by increasing the growth rate of surviving trees, and 2) by inducing mortality of small, suppressed trees. In turn, the growth rate of surviving trees depends on the amount of nitrogen applied and the space available for crown expansion. Differences in response to F_1 and F_2 and to refertilization were greatest in the T_2 plots, where the trees have had space in which to expand their crowns. There were larger differences in response to additional amounts of fertilizer in the unthinned plots than in the moderately thinned plots. This was probably caused by the much higher levels of mortality due to suppression in the unthinned plots. In the moderately thinned plots, increases in the quantity of fertilizer only resulted in slight increases in quadratic mean diameter. This may be because the trees did not have enough space for crown expansion to take full advantage of the additional fertilizer.

Thinning alone increased quadratic mean diameter much more than fertilization alone. The heaviest dose of fertilizer without thinning ($T_0F_{2\text{-}2}$) produced an adjusted quadratic mean diameter at year 15 of 16.0 cm, while heavy thinning alone (T_2F_0) resulted in an adjusted quadratic mean diameter of 18.9 cm (18% larger). The combination of heavy thinning and heavy fertilization ($T_2F_{2\text{-}2}$) produced trees with the largest diameters (23.3 cm adjusted quadratic mean diameter); such trees were 1.8 times the diameter of the smallest trees which were found in the control plots (12.6 cm adjusted quadratic mean diameter).

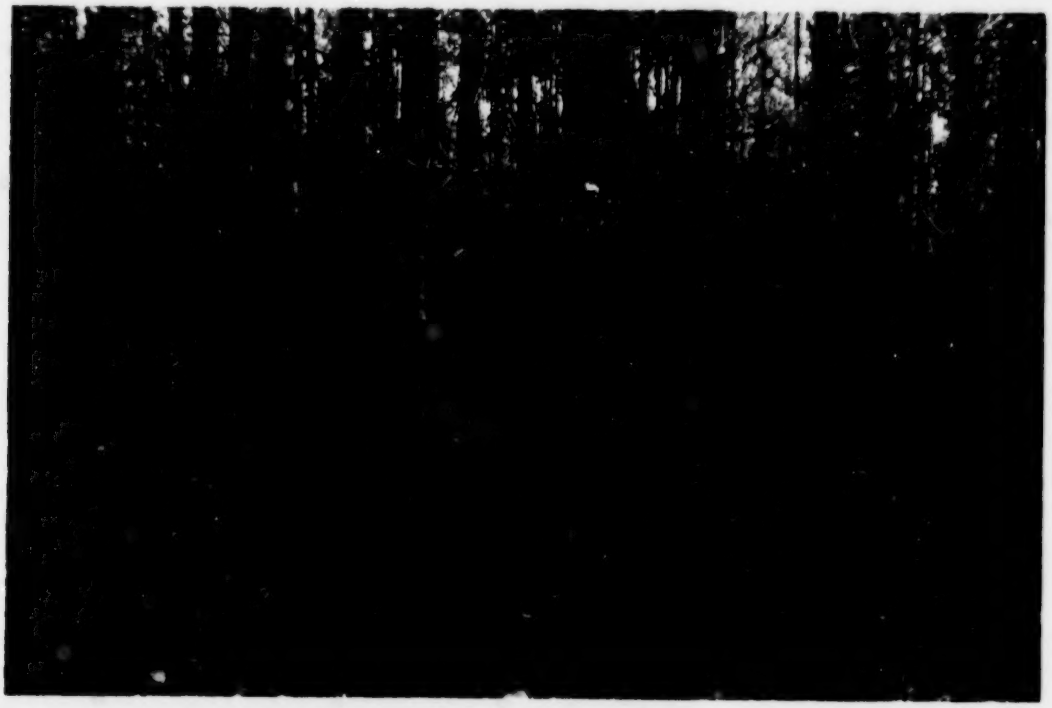
Table 3. Number of live stems per hectare by treatment and year

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T_0F_0	4852	4852	4796	4734	4623	4493	4283
T_0F_1	3572	3572	3535	3461	3375	3152	2979
T_0F_{1-1}	3684	3684	3560	3263	3041	2806	2522
T_0F_2	4042	4042	3980	3634	3325	3066	2855
T_0F_{2-2}	3226	3226	3189	2942	2744	2522	2262
T_1F_0	4357	1972	1959	1953	1941	1941	1922
T_1F_1	3473	1817	1817	1805	1792	1780	1718
T_1F_{1-1}	3758	1891	1891	1891	1891	1854	1805
T_1F_2	4104	2015	2015	1965	1941	1916	1916
T_1F_{2-2}	3832	2089	2089	2040	1978	1904	1768
T_2F_0	3776	896	896	896	896	896	896
T_2F_1	3931	939	939	939	939	939	915
T_2F_{1-1}	3758	890	878	878	878	878	865
T_2F_2	3684	915	915	915	915	915	915
T_2F_{2-2}	4042	878	865	865	865	865	853

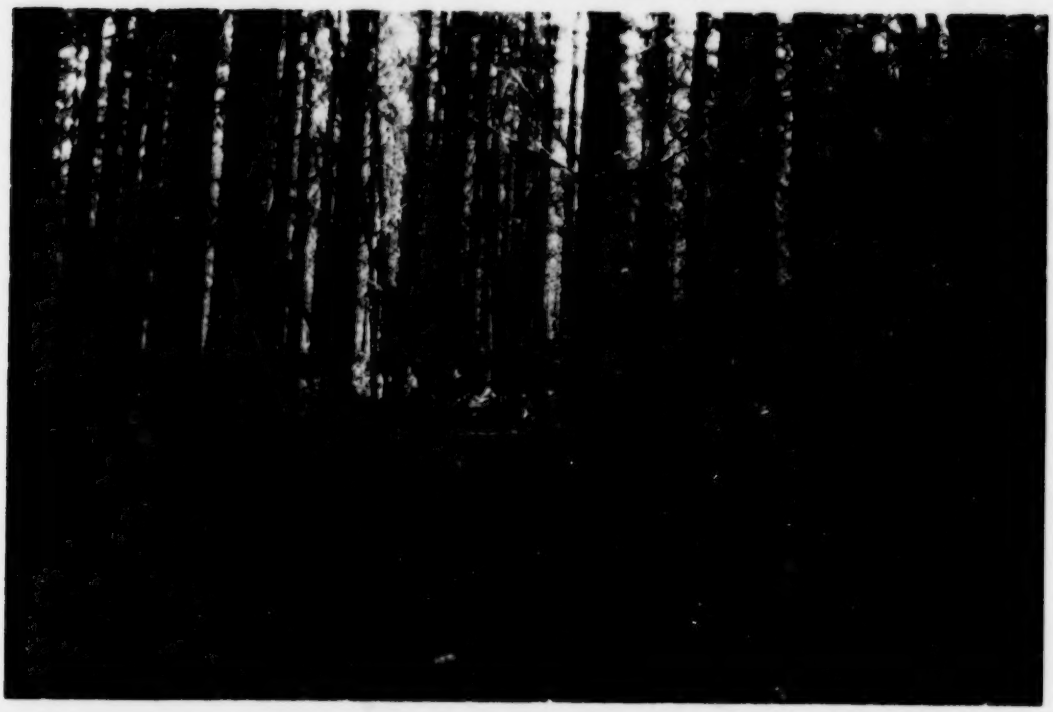
Table 4. Number and quadratic mean diameter* (dbhq) of trees that died

Treatment	Year									
	0 - 3		3 - 6		6 - 9		9 - 12		12 - 15	
	Trees/ha	dbhq (cm)	Trees/ha	dbhq (cm)	Trees/ha	dbhq (cm)	Trees/ha	dbhq (cm)	Trees/ha	dbhq
T_0F_0	56	4.9	62	5.8	111	8.0	130	4.9	210	4.7
T_0F_1	37	3.0	74	4.9	87	4.1	222	5.3	173	6.6
T_0F_{1-1}	124	4.8	297	5.1	222	7.4	235	5.7	284	8.2
T_0F_2	62	3.3	346	4.4	309	5.4	260	7.0	210	7.5
T_0F_{2-2}	37	8.8	247	5.7	198	6.8	222	6.2	260	10.1
T1F0	12	6.6	6	9.4	12	9.5	0	-	19	10.1
T_1F_1	0	-	12	8.1	12	3.9	12	5.5	62	12.0
T_1F_{1-1}	0	-	0	-	0	-	37	6.4	49	7.7
T_1F_2	0	-	49	8.3	25	4.6	25	6.5	0	-
T_1F_{2-2}	0	-	49	7.8	62	7.4	74	8.1	136	11.2
T_2F_0	0	-	0	-	0	-	0	-	0	-
T_2F_1	0	-	0	-	0	-	0	-	25	11.4
T_2F_{1-1}	12	9.3	0	-	0	-	0	-	12	11.7
T_2F_2	0	-	0	-	0	-	0	-	0	-
T_2F_{2-2}	12	9.5	0	-	0	-	0	-	12	15.4

*Based on diameters at beginning of each period.

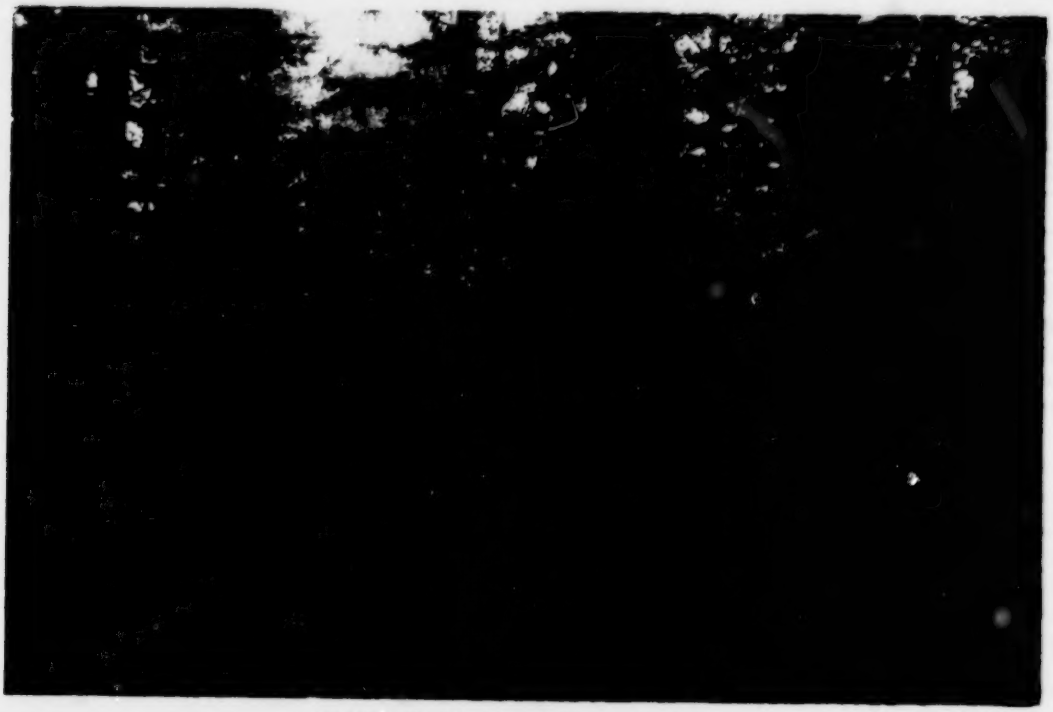


(a) A control plot, no treatments applied (T_0F_0). .

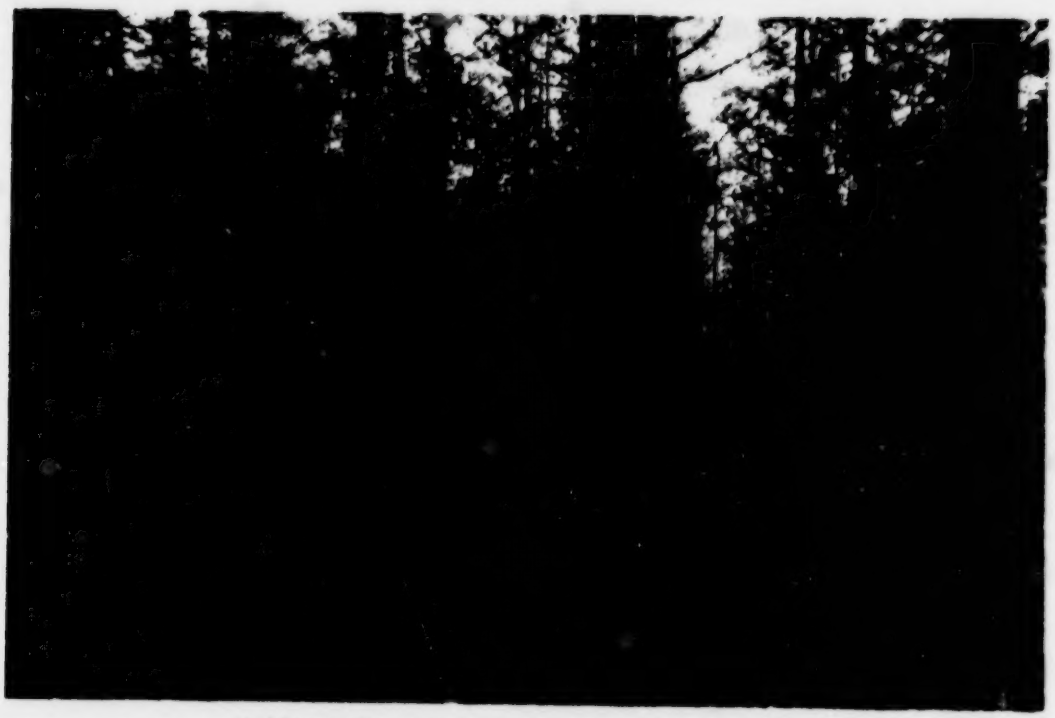


(b) An unthinned plot fertilized once with 448 kg N/ha (T_0F_2)

Figure 2. The effects of thinning and urea fertilization 15 years after treatment.



(c) A heavily thinned, unfertilized plot (T_2F_0).



(d) A heavily thinned plot fertilized once with 448 kg N/ha (T_2F_2).

Figure 2 (continued). The effects of thinning and urea fertilization 15 years after treatment.

Table 5. Causes of mortality to year 15

Treatment	Suppression	Snow damage	White pine blister rust	Root rot	Mechanical	unknown	Total mortality	Percent mortality
				Stems/ha				
T_0F_0	501	31	12	0	6	19	569	11.7
T_0F_1	544	49	0	0	0	0	593	16.6
T_0F_{1-1}	1088	49	12	0	0	12	1162	31.5
T_0F_2	1175	0	12	0	0	0	1187	29.4
T_0F_{2-2}	791	112	49	0	0	12	964	29.9
T_1F_0	12	19	0	19	0	0	50	2.5
T_1F_1	37	62	0	0	0	0	99	5.4
T_1F_{1-1}	86	0	0	0	0	0	86	4.5
T_1F_2	62	25	0	0	0	12	99	4.9
T_1F_{2-2}	247	74	0	0	0	0	321	15.4
T_2F_0	0	0	0	0	0	0	0	0.0
T_2F_1	0	25	0	0	0	0	25	2.7
T_2F_{1-1}	0	25	0	0	0	0	25	2.8
T_2F_2	0	0	0	0	0	0	0	0.0
T_2F_{2-2}	0	25	0	0	0	0	25	2.8

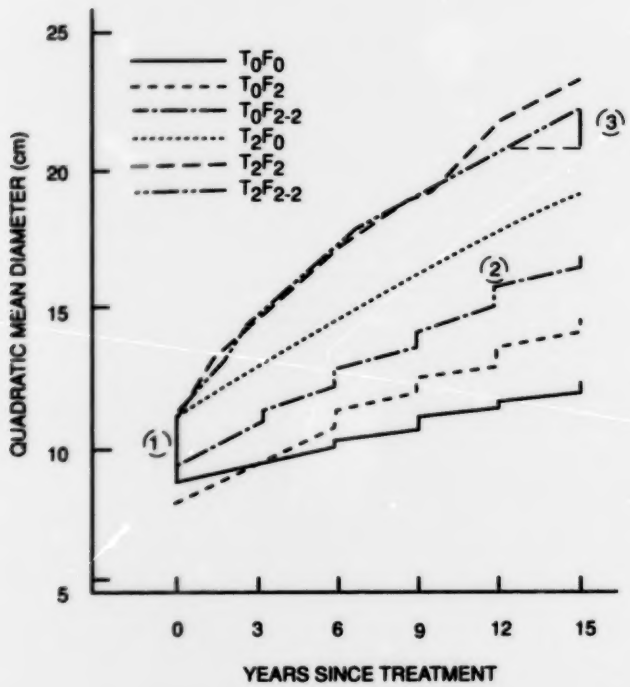


Figure 3. Factors influencing quadratic mean diameter.
1 Arithmetic increase from removal of smaller trees at time of thinning.
2 Arithmetic increase from trees dying over the specified period.
3 Increased growth rate due to treatment.

Table 6a. Quadratic mean diameter (cm) by treatment and year[1]

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T_0F_0	8.4	8.4	9.2	9.8	10.5	11.2	11.9
T_0F_1	9.0	9.0	10.2	11.2	12.0	13.2	14.0
T_0F_{1-1}	9.3	9.3	10.8	12.1	13.1	14.6	15.8
T_0F_2	7.8	7.8	9.4	10.9	12.0	13.2	14.2
T_0F_{2-2}	9.1	9.1	10.8	12.4	13.7	15.4	16.8
T_1F_0	8.4	10.0	11.3	12.4	13.5	14.5	15.3
T_1F_1	8.9	10.1	12.0	13.4	14.6	15.8	16.8
T_1F_{1-1}	9.2	10.5	12.5	13.7	15.0	16.4	17.6
T_1F_2	8.2	9.6	12.0	13.8	15.1	16.3	17.1
T_1F_{2-2}	9.5	10.1	12.5	14.2	15.6	17.3	18.7
T_2F_0	8.5	10.8	12.7	14.4	16.0	17.5	18.7
T_2F_1	8.8	10.8	13.8	15.8	17.5	19.1	20.6
T_2F_{1-1}	8.4	11.0	14.0	16.0	17.8	19.9	21.5
T_2F_2	8.3	10.8	14.5	17.1	18.9	20.6	22.0
T_2F_{2-2}	8.4	11.1	14.6	17.0	18.9	21.4	23.1

Table 6b. Periodic annual diameter increments (cm/yr) for each treatment combination[2]

Treatment	Year							
	0-3	3-6	6-9	9-12	12-15	0-15	0-9	9-15
T_0F_0	0.23	0.18	0.17	0.17	0.13	0.18	0.19	0.15
T_0F_1	0.36	0.25	0.19	0.23	0.17	0.26	0.28	0.20
T_0F_{1-1}	0.39	0.26	0.23	0.28	0.20	0.32	0.31	0.26
T_0F_2	0.48	0.33	0.23	0.25	0.19	0.34	0.38	0.22
T_0F_{2-2}	0.52	0.37	0.29	0.38	0.26	0.42	0.42	0.34
T_1F_0	0.40	0.36	0.34	0.32	0.24	0.33	0.37	0.28
T_1F1	0.63	0.43	0.38	0.37	0.27	0.42	0.48	0.32
T_1F_{1-1}	0.66	0.39	0.38	0.42	0.29	0.44	0.48	0.36
T_1F_2	0.79	0.54	0.38	0.35	0.26	0.47	0.58	0.31
T_1F_{2-2}	0.75	0.51	0.37	0.46	0.31	0.51	0.55	0.40
T_2F_0	0.61	0.57	0.52	0.50	0.39	0.52	0.57	0.45
T_2F_1	0.98	0.66	0.57	0.53	0.41	0.64	0.74	0.47
T_2F_{1-1}	0.99	0.65	0.60	0.69	0.48	0.68	0.75	0.58
T_2F_2	1.22	0.87	0.60	0.57	0.45	0.74	0.90	0.51
T_2F_{2-2}	1.15	0.81	0.62	0.80	0.54	0.79	0.86	0.67

[1] These averages will differ slightly from previous reports because all species, not just Douglas-fir, are included.

[2] Trees dying during specified time period were excluded from the average.

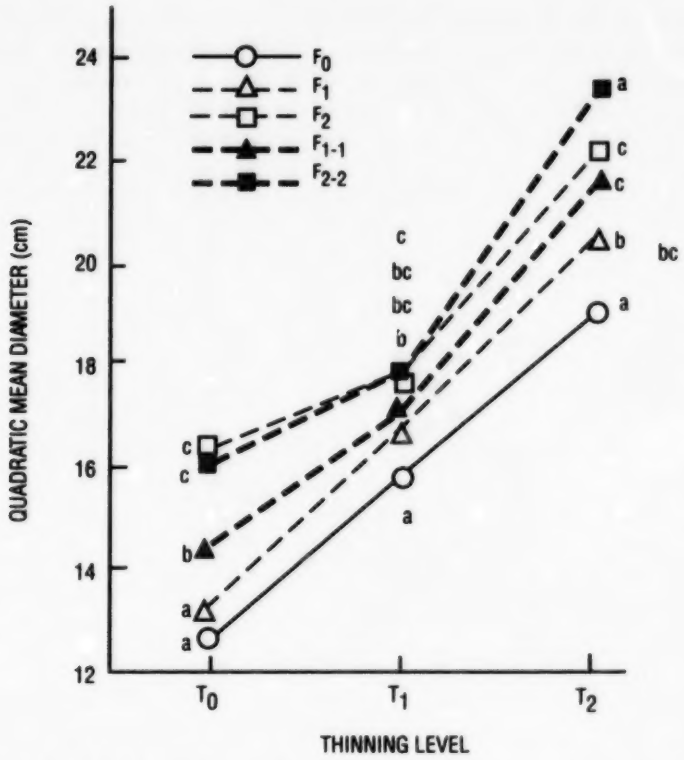


Figure 4. Adjusted quadratic mean diameter for each treatment combination 15 years after initial treatment. Quadratic mean diameter prior to treatment was used as the covariate to adjust quadratic mean diameter at year 15. Within each thinning level, diameters followed by the same letter are not significantly different ($p \leq 0.05$).

4.2.2 Periodic annual diameter increment

Periodic annual diameter increments are presented in Table 6b, and represent the average annual diameter growth of all trees living to the end of each specified period. These values are lower than those previously published (Barclay and Brix 1985a), since previous values included an arithmetic increase in average diameter from the death of small, suppressed trees over the specified time period.

Across all treatments, the average annual diameter increment from year 12 to year 15 was lower than that from year 9 to year 12. However, in each thinning level the refertilized plots were still growing faster than those fertilized only once. The heavily thinned plots continued to show the best annual diameter growth. All treatments showed a lower average diameter growth rate from year 9 to year 15 year than in the first 9 years, but refertilization offset this decline (Table 6b). It was in the T_2 plots that refertilization had the greatest effect in reducing the overall decline in diameter growth rate between years 9 and 15.

4.2.3 Diameter growth response of trees of similar initial size

Average periodic annual diameter increments (0 to 15 years) by initial 5-cm dbh classes are shown in Figure 5. Dbh classes were chosen to represent the initial dbh classes common to all treatments, and not the full range of diameters present. In all treatments there is a pattern of increasing annual growth rate with increasing initial size. However, the smallest trees (those in the 5 to 10 cm initial dbh class) have benefited the most in terms of increased diameter growth relative to the control trees, and thinning increased diameter growth of the smallest trees more than fertilization. The greatest response in all three dbh classes occurred in the T_2F_{2-2} plots. The trees with an initial dbh of 15 to 20 cm increased in

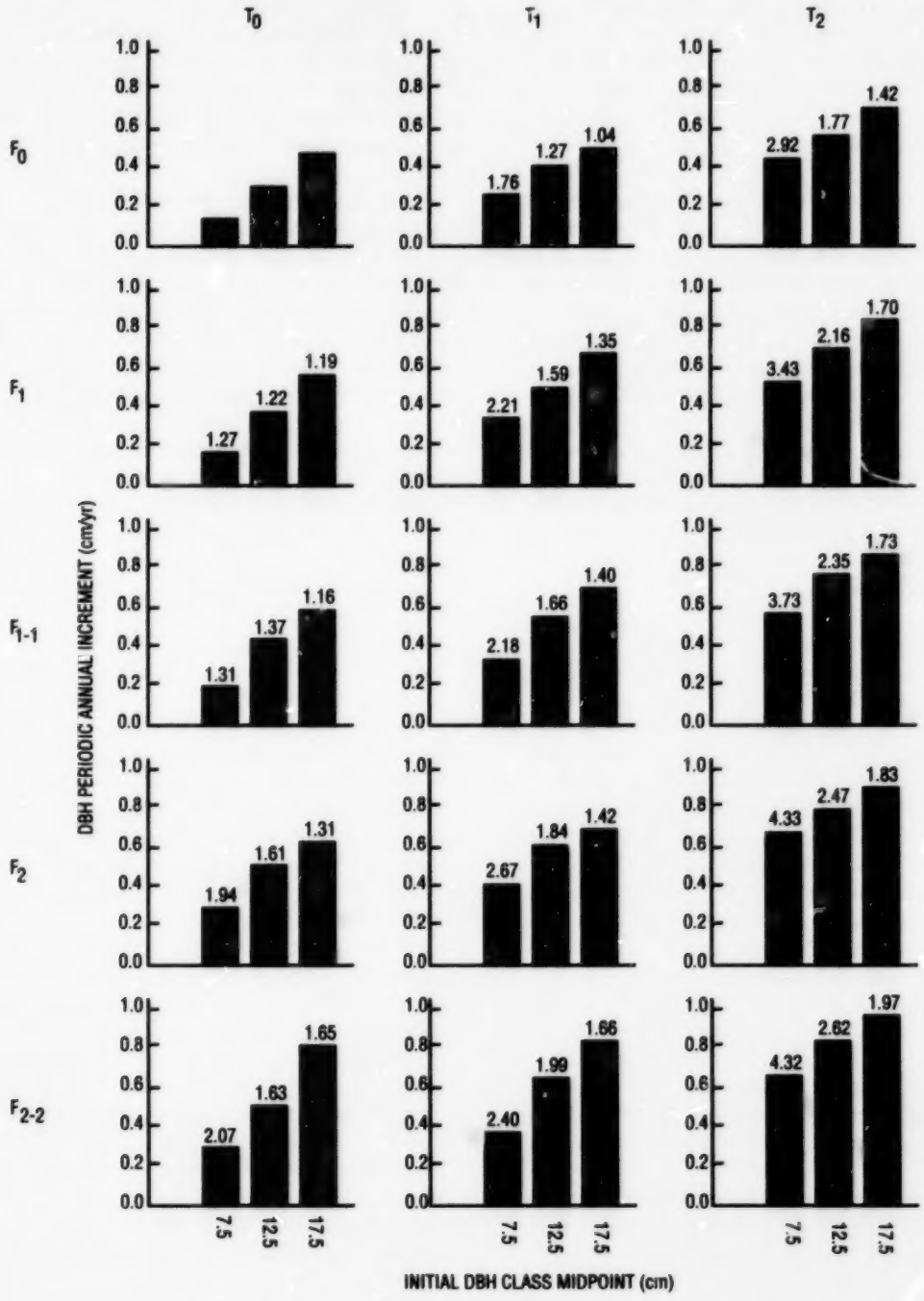


Figure 5. Average annual diameter increment for each treatment combination between years 0 and 15 by 5-cm dbh classes. Trees were placed into dbh classes based on their initial diameters at year 0. The numbers above the bars indicate the factor by which diameter increment increased relative to trees of similar initial size in the control (T_0F_0) plot.

diameter about twice as fast as control trees of similar initial size; those with an initial dbh of 10 to 15 cm grew almost three times faster; and those with an initial dbh of 5 to 10 cm grew over four times faster than control trees of similar initial size.

4.2.4 Diameter distribution

The diameter distribution at year 15 for each of the treatments is shown in Figure 6. As expected, heavier thinning combined with any level of fertilization has resulted in more uniform diameter distributions. Fertilization has had a lesser but similar effect in the unthinned treatments by accelerating mortality due to suppression.

At year 15, the majority of trees in the control plots were still in the 5 to 15 cm diameter range. The greatest contrast occurred in the $T_2F_{2\text{-}2}$ plots, where the majority of the trees were in the 20 to 30 cm range. Both thinning and fertilization shifted the distribution to larger diameters.

4.2.5 Crop tree response

An analysis of covariance on the diameters of both the 250 and 500 crop trees showed a significant positive effect from both thinning and fertilization without an interaction between treatments (Appendix Tables A4 and A5). There was a trend of increased diameter with increasing amounts of fertilizer, but in general there were no significant differences between the refertilized trees and those fertilized only once ($F_{1\text{-}1}$ vs F_2). However, the F_2 treatment resulted in significantly larger trees than the F_1 treatment. Averaged across all thinning levels, the 500 F_2 crop trees were 7% (1.4 cm) larger than the 500 F_1 crop trees, and the 250 F_2 crop trees were 6% (1.3 cm) larger than the 250 F_1 crop trees. All levels of fertilization resulted in significantly larger diameters than in the control. The adjusted average diameters for the 250 and 500 crop trees at year 15 are presented in Appendix Table A16.

For the 250 crop trees, the intermediate level of thinning (T_1) did not produce trees of significantly larger diameter than in the unthinned plots (T_0). However, heavy thinning (T_2) resulted in significantly larger diameters than in either of the T_0 or T_1 treatments. Averaged across all fertilizer levels, the T_2 trees were 12% (2.7 cm) larger in diameter than the T_1 trees and 16% (3.6 cm) larger than the T_0 trees.

This pattern changed when the 500 crop trees were considered. Each increased level of thinning resulted in significantly larger diameters. Averaged across all fertilizer levels, the T_2 trees were 13% (2.8 cm) larger in diameter than the T_1 trees and 20% (4 cm) larger in diameter than the T_0 trees. The T_1 trees were 6% (1.2 cm) larger in diameter than the T_0 trees.

In contrast to the results obtained for all core trees (where quadratic mean diameter was increased more by thinning than fertilization), the effects of thinning and fertilization on average quadratic mean diameter for the 250 and 500 crop trees did not differ. For example, the average diameter in the T_0F_2 plots was not significantly different from those in the T_2F_0 plots. The different results between the core and crop trees are due to the influence of several small trees on the core plot average. Figure 7 compares the quadratic mean diameter of the core trees with those of the 250 and 500 crop trees for the six extreme treatments.

4.3 Total basal area

An analysis of covariance on total basal area per hectare at year 15 showed significant effects of thinning and fertilization, without an interaction between the two treatments (Appendix Table A6). Thinning has decreased total basal area while fertilization has increased it. Total basal area per hectare and periodic annual increments by treatment and year are presented in Table 7. Adjusted means are listed in Appendix Table A16. In general, the following statements can be made:

(1) The unthinned plots had more basal area than the thinned plots, and the moderately thinned plots had more basal area than the heavily thinned plots. Based on adjusted totals and averaged over all fertilization levels, the T_0 plots had 15% (6.05 m^2/ha) more basal area per hectare than the T_1 plots and 49% (15.71 m^2/ha) more than the T_2 plots. The T_1 plots had 30% (9.66 m^2/ha) more basal area than the T_2 plots.

(2) In each thinning level any one of the four fertilization treatments increased the basal area over that in the unfertilized plots.

(3) The F_2 level of fertilizer resulted in more basal area than the F_1 level. Based on adjusted totals and averaged over all thinning levels the F_2 plots had 12% (4.58 m^2/ha) more basal area at year 15 than the F_1 plots.

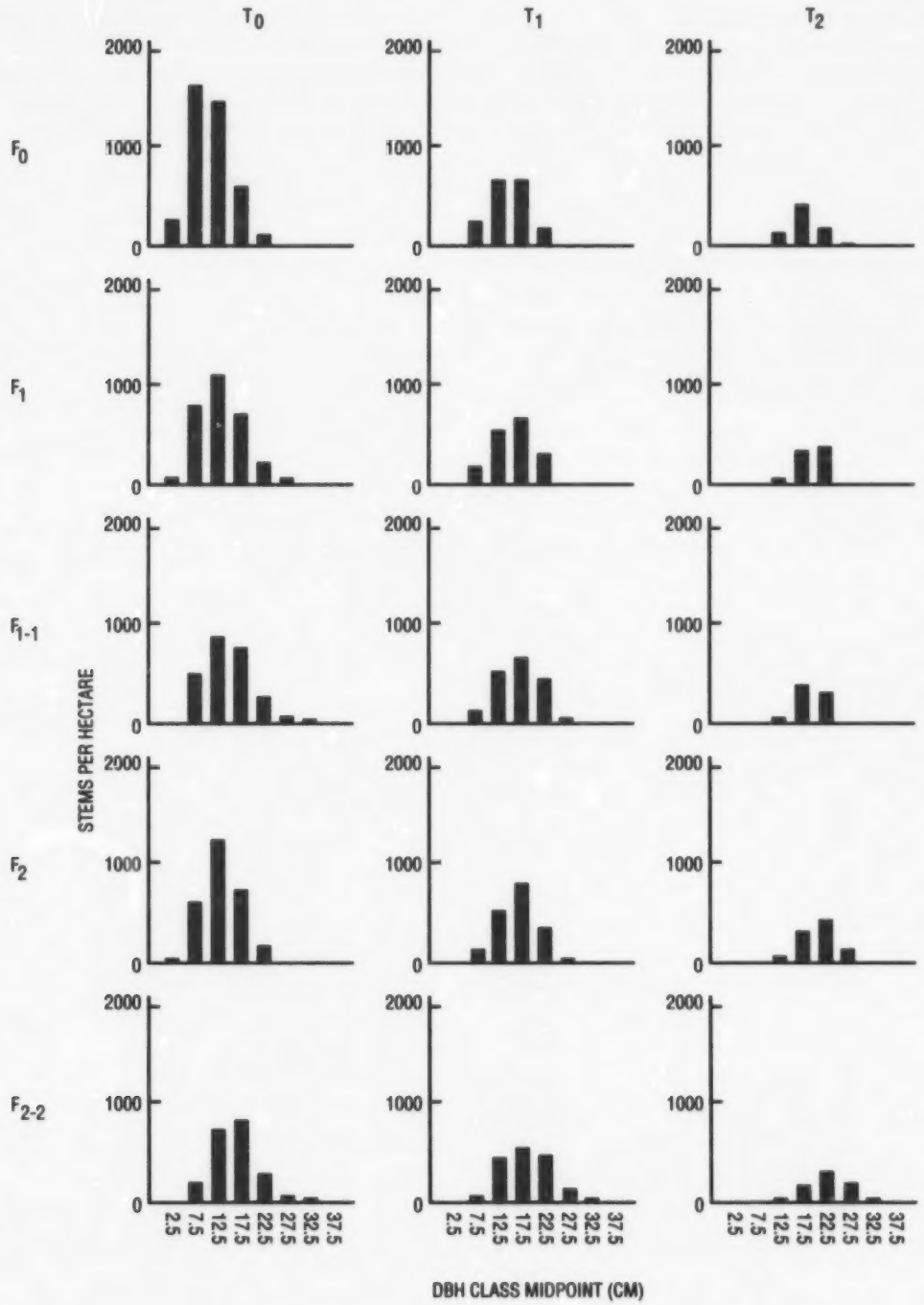


Figure 6. Diameter distribution for each treatment combination by 5-cm dbh class 15 years after initial treatment

(4) The refertilized plots had more basal area than those fertilized only once, but at year 15 these differences were not significant.

(5) At year 15, the most basal area was in the T_0F_{2-2} plots while the least was in the T_2F_0 plots. Based on adjusted totals, the difference was 25.02 m^2/ha; the T_0F_{2-2} plots had twice the basal area of the T_2F_0 plots.

For all treatments, the periodic annual increment from year 12 to 15 was less than that for years 9 to 12. The refertilized plots, which had significant increases in annual growth rates from year 9 to year 12, showed the greatest decline. This trend of declining periodic annual increment varied among thinning levels; the largest decrease occurred in the unthinned plots, while the smallest decrease occurred in the heavily thinned plots.

The effect of fertilizer on annual basal area growth rate over the period from year 12 to year 15 varied among thinning levels. In the T_0 plots, no level of fertilization resulted in a greater annual growth rate than that in the unfertilized plots. In the T_1 plots, all levels of fertilization (except F_1) resulted in greater annual growth rates. In the T_2 plots, all fertilized plots continued to grow at a faster rate than the unfertilized plots.

A comparison of the periodic annual increments before and after refertilization showed that the average annual growth rate declined after year 9 in all treatments, except in the heavily thinned refertilized plots. In the T_0 and T_1 plots, this decline in annual basal area growth rate after year 9 was less in the refertilized plots than in other plots.

4.4 Height

Plots were compared on the basis of average stand height, average annual height growth up to year 15, and annual top height growth up to year 9. Differences in average heights are the result of growth differences between treatments, an immediate arithmetic increase from the removal of small trees at the time of thinning, and subsequent increases from mortality of suppressed trees in the

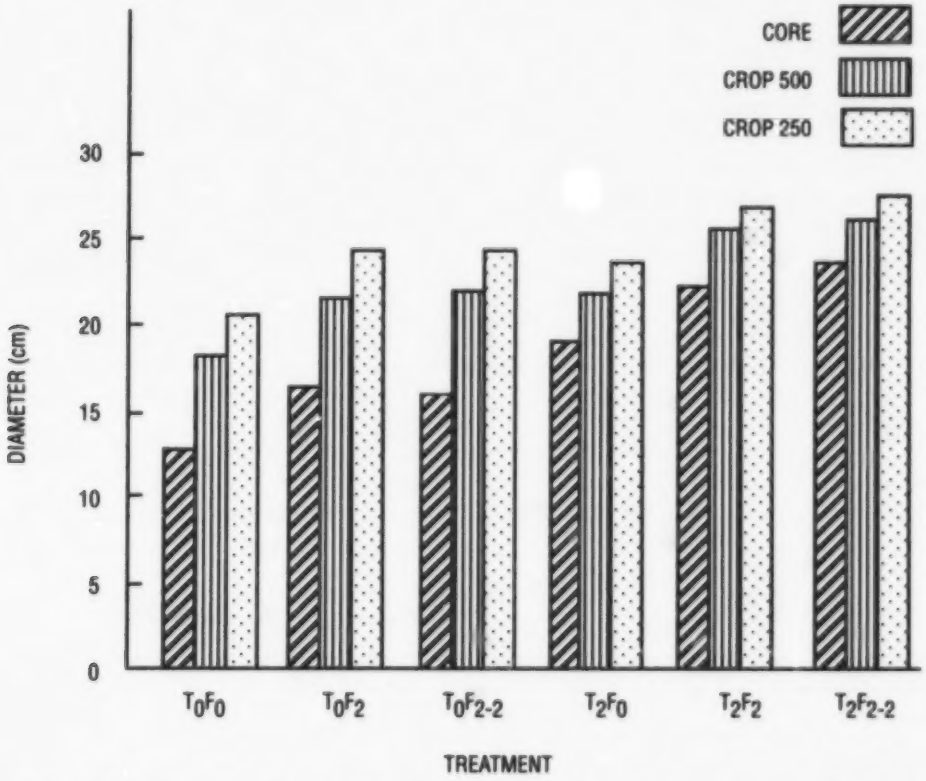


Figure 7. Adjusted quadratic mean diameter of the core and crop trees for the six extreme treatments 15 years after initial treatment

Table 7a. Basal area (m^2/ha) by treatment and year

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T_0F_0	26.6	26.6	31.7	35.9	39.7	44.1	47.3
T_0F_1	22.7	22.7	29.1	34.1	38.2	42.9	46.1
T_0F_{1-1}	25.2	25.2	32.5	37.2	41.2	46.8	49.7
T_0F_2	19.1	19.1	27.5	33.7	37.8	41.9	45.0
T_0F_{2-2}	21.1	21.1	29.3	35.4	40.2	47.0	50.1
T_1F_0	24.0	15.6	19.7	23.7	27.7	32.1	35.4
T_1F_1	21.5	14.5	20.6	25.4	30.1	35.1	38.2
T_1F_{1-1}	24.9	16.3	23.2	28.0	33.2	39.4	43.7
T_1F_2	21.8	14.6	22.8	29.3	34.6	39.9	44.1
T_1F_{2-2}	27.2	16.8	25.5	32.2	37.6	44.7	48.6
T_2F_0	21.4	8.3	11.3	14.6	18.0	21.6	24.7
T_2F_1	24.2	8.6	14.0	18.3	22.6	27.0	30.4
T_2F_{1-1}	20.9	8.5	13.6	17.7	22.0	27.4	31.4
T_2F_2	20.0	8.4	15.0	21.0	25.7	30.6	34.8
T_2F_{2-2}	22.7	8.5	14.4	19.7	24.4	31.1	35.8

Table 7b. Net periodic annual basal area increments (m^2/ha/yr) for each treatment combination

Treatment	Year							
	0-3	3-6	6-9	9-12	12-15	0-15	0-9	9-15
T_0F_0	1.70	1.40	1.27	1.47	1.07	1.38	1.46	1.27
T_0F_1	2.13	1.67	1.37	1.57	1.07	1.56	1.72	1.32
T_0F_{1-1}	2.43	1.57	1.33	1.87	0.97	1.63	1.78	1.42
T_0F_2	2.80	2.07	1.37	1.37	1.03	1.73	2.08	1.20
T_0F_{2-2}	2.73	2.03	1.60	2.27	1.03	1.93	2.12	1.65
T_1F_0	1.37	1.33	1.33	1.47	1.10	1.32	1.34	1.28
T_1F_1	2.03	1.60	1.57	1.67	1.03	1.58	1.73	1.35
T_1F_{1-1}	2.30	1.60	1.73	2.07	1.43	1.83	1.88	1.75
T_1F_2	2.73	2.17	1.77	1.77	1.40	1.97	2.22	1.58
T_1F_{2-2}	2.90	2.23	1.80	2.37	1.30	2.12	2.31	1.83
T_2F_0	1.00	1.10	1.13	1.20	1.03	1.09	1.08	1.12
T_2F_1	1.80	1.43	1.43	1.47	1.13	1.45	1.56	1.30
T_2F_{1-1}	1.70	1.37	1.43	1.80	1.33	1.53	1.50	1.57
T_2F_2	2.20	2.00	1.57	1.63	1.40	1.76	1.92	1.52
T_2F_{2-2}	1.97	1.77	1.57	2.23	1.57	1.82	1.77	1.90

unthinned plots. The comparison of average annual height growth removes these arithmetic increases, and the comparison of top height growth further removes the influence of smaller surviving trees which otherwise lower the average height growth in the unthinned plots relative to the thinned plots.

4.4.1 Average height

Both fertilization and thinning significantly increased the average height at year 15 (Figure 8, Table 8a, Appendix Table A16), without an interaction between the two treatments (Appendix Table A7). All fertilized plots had significantly greater adjusted average heights than the control plots. Within the fertilized plots, there was a trend of increased average height with increasing amounts of fertilizer, but this was not significant.

4.4.2 Periodic annual height growth

The average periodic annual height growth in all treatments from year 12 to year 15 was less than that from year 9 to year 12 (Table 8b). However, in each thinning level, all fertilized trees continued to grow faster than the unfertilized trees, and the refertilized trees continued to grow faster than those fertilized only once. In comparing annual average height growth before and after refertilization, the following observations were made:

(1) In the unthinned plots, the annual height growth of all trees declined after year 9, and the refertilized trees had the smallest decrease in growth rate.

(2) In the moderately thinned plots, the refertilized trees continued to grow at the same rate after year 9, the unfertilized trees grew faster after year 9, and trees that were fertilized once grew slower.

(3) In the heavily thinned plots, all trees had a greater average annual height growth after year 9 than before year 9, and the unfertilized and the refertilized trees showed the greatest increases.

4.4.3 Top height growth

Top height is defined as the average height of the 100 trees per hectare that have the largest diameter, and is approximated by the average height of the four trees on each 0.0405-ha plot that have the largest diameter. Since heights were measured on all

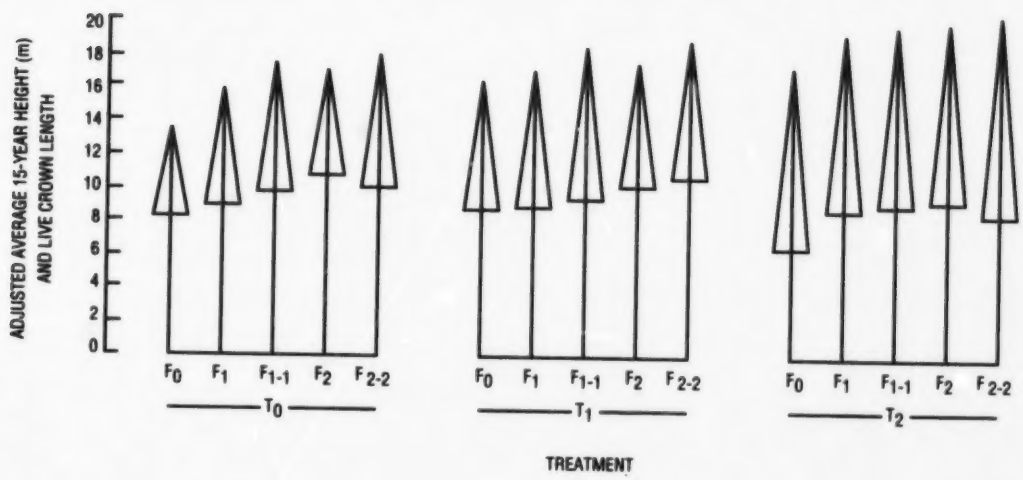


Figure 8. Adjusted average heights and average live crown lengths for each treatment combination 15 years after initial treatment. Crown widths are not drawn to scale.

Table 8a. Average heights (m) by treatment and year[1]

Treatment	Year					
	0	3	6	9	12	15
T_0F_0	8.4	9.5	10.4	11.3	12.1	13.2
T_0F_1	8.7	10.2	11.4	12.4	14.2	15.8
$T_0F_{1\text{-}1}$	9.3	10.8	12.8	14.8	16.7	17.8
T_0F_2	7.9	9.7	11.4	12.5	13.8	15.4
$T_0F_{2\text{-}2}$	8.9	10.6	12.4	14.4	16.3	17.8
T_1F_0	9.8	10.9	12.0	13.1	14.4	15.4
T_1F_1	9.2	11.0	12.4	13.7	15.5	16.6
$T_1F_{1\text{-}1}$	10.4	12.2	13.4	15.0	16.9	18.5
T_1F_2	8.4	10.3	12.0	13.4	15.3	16.5
$T_1F_{2\text{-}2}$	10.2	12.1	14.2	15.8	18.0	19.9
T_2F_0	9.9	10.9	12.2	13.6	15.3	16.9
T_2F_1	10.6	12.5	14.3	15.8	17.8	19.5
$T_2F_{1\text{-}1}$	10.5	12.3	13.9	15.7	18.0	20.0
T_2F_2	9.8	12.0	14.0	15.6	17.6	19.4
$T_2F_{2\text{-}2}$	10.3	12.2	13.8	15.7	18.2	20.3

Table 8b. Periodic annual height increments (m/yr) for each treatment combination[2]

Treatment	Year							
	0-3	3-6	6-9	9-12	12-15	0-15	0-9	9-15
T_0F_0	0.34	0.26	0.21	0.25	0.20	0.27	0.30	0.23
T_0F_1	0.50	0.38	0.23	0.37	0.33	0.41	0.44	0.36
$T_0F_{1\text{-}1}$	0.52	0.39	0.43	0.53	0.38	0.49	0.51	0.45
T_0F_2	0.60	0.47	0.29	0.42	0.34	0.47	0.51	0.40
$T_0F_{2\text{-}2}$	0.57	0.40	0.43	0.59	0.45	0.52	0.53	0.52
T_1F_0	0.39	0.36	0.35	0.44	0.35	0.38	0.37	0.40
T_1F_1	0.60	0.48	0.35	0.53	0.38	0.48	0.49	0.46
$T_1F_{1\text{-}1}$	0.58	0.42	0.46	0.56	0.44	0.51	0.51	0.51
T_1F_2	0.65	0.54	0.37	0.55	0.41	0.52	0.55	0.48
$T_1F_{2\text{-}2}$	0.65	0.56	0.54	0.66	0.53	0.61	0.61	0.61
T_2F_0	0.34	0.42	0.46	0.59	0.52	0.47	0.41	0.56
T_2F_1	0.64	0.61	0.50	0.65	0.56	0.59	0.58	0.61
$T_2F_{1\text{-}1}$	0.60	0.54	0.59	0.78	0.64	0.63	0.58	0.71
T_2F_2	0.76	0.65	0.52	0.69	0.58	0.64	0.64	0.64
$T_2F_{2\text{-}2}$	0.62	0.54	0.63	0.84	0.65	0.66	0.60	0.75

[1] These values will differ slightly from previous reports as they are based on only volume and extra height trees.
[2] Trees dying during specified time period were excluded from the average.

trees only until 9 years after treatment, a representative sample from each plot could be obtained for only the first 9 years (Figure 9)[4].

Top height growth tended to increase as stand density decreased, but an analysis of variance for the first 9 years of top height growth did not show a significant effect of thinning (Appendix Table A8). However, a reduction in height growth, commonly termed thinning shock, was apparent for the first 3 years after thinning (Crown et al. 1977). When analyzed over the period from year 3 to year 9, thinning had a significant effect on top height growth (Appendix Table A9).

Fertilization markedly increased top height growth. Averaged over all thinning levels, the top height trees in the F_1 plots grew an average of 14 cm more per year than the unfertilized plots, while the trees in the F_2 plots grew an average of 17 cm more per year. As was the case with average height growth, more fertilizer resulted in taller trees, but no significant differences could be detected between the F_1 and F_2 trees.

4.4.4 Height distribution

Summaries of height distribution at year 15 are based on the volume and extra height trees. As these trees were selected to represent the range of diameters present within a given treatment, their height distribution should reflect the overall height distribution. Thinning reduced the range of heights from 20.9 m in the control plots to only 4.7 m in the T_2F_2 plots (Table 9).

Table 9. Ranges of heights (m) 15 years after treatment (based on volume and extra height trees)

Fertilization Level	Thinning Level		
	T_0	T_1	T_2
F_0	4.1 - 25.0	7.2 - 21.6	12.4 - 22.0
F_1	7.2 - 22.2	7.2 - 23.1	14.7 - 23.0
$F_{1\text{-}1}$	11.5 - 26.2	10.7 - 24.2	16.2 - 25.4
F_2	9.1 - 20.4	9.2 - 20.6	17.1 - 21.8
$F_{2\text{-}2}$	11.2 - 23.1	13.4 - 24.1	16.7 - 23.0

4. As the 1972 plots were refertilized following the measurements at year 9, this analysis does not include the effects of refertilization.

4.5 Live crown length

Average live crown lengths and percent live crown by treatment and year are presented in Table 10 and illustrated in Figure 8. The longest live crowns and the greatest percent live crown were found in the heavily thinned plots. The shortest live crowns were in the control plots and were approximately half the length of those found in the heavily thinned and fertilized plots.

4.6 Volume

4.6.1 Total volume and volume increments per hectare

An analysis of covariance on total volume per hectare at year 15 showed significant effects of both thinning and fertilization, without an interaction between the two treatments (Appendix Table A10). Total volumes per hectare and periodic annual increments by treatment and year are presented in Table 11.

Thinning resulted in significant decreases in total volume at year 15, whereas fertilization resulted in significant increases. Figure 10 shows adjusted total volumes per hectare at year 15 by thinning and fertilization level. Based on adjusted totals, the treatments which resulted in the greatest total volume were $T_1F_{2\text{-}2}$ (458 m^3/ha) and $T_0F_{2\text{-}2}$ (456 m^3/ha). The treatment which resulted in the lowest adjusted volume was T_2F_0 (221 m^3/ha). This represents a difference of 237 m^3/ha. In general, the following statements can be made about adjusted total volume per hectare 15 years after the initial treatment:

(1) The unthinned plots had a greater total volume than the thinned plots. Averaged across all fertilization levels the T_0 plots had 9% (35 m^3/ha) and 36% (108 m^3/ha) more volume than the T_1 and T_2 plots, respectively.

(2) The moderately thinned (T_1) plots had a greater total volume than the heavily thinned (T_2) plots. Averaged over all fertilization levels, the T_1 plots had 24% (73 m^3/ha) more volume.

(3) All levels of fertilization resulted in greater total volumes than the unfertilized plots. Averaged over all thinning levels, increases in total volumes were as follows: F_1 17% (49 m^3/ha); $F_{1\text{-}1}$ 32% (94 m^3/ha); F_2 32% (92 m^3/ha); $F_{2\text{-}2}$ 45% (131 m^3/ha).

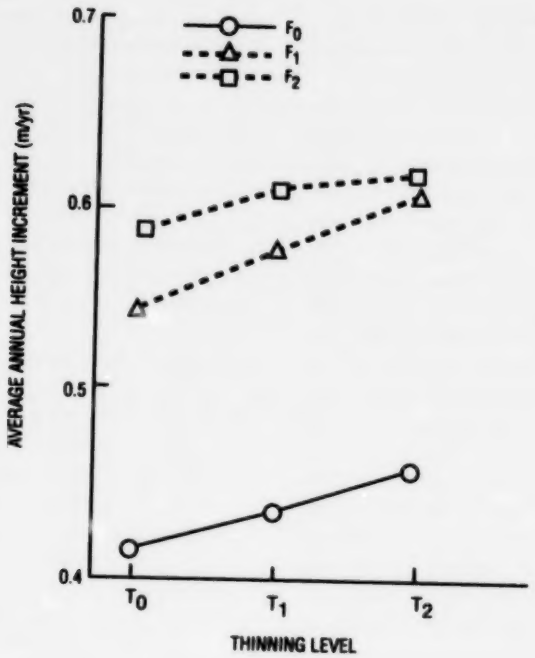


Figure 9. Average annual height increments of the top height trees during the first 9 years after initial treatment.

Table 10. Average percent live crown and live crown length by treatment and year[1]

Treatment	Year							
	0 After		6		9		15	
	Live crown (%)	Live crown length (m)	Live crown (%)	Live crown length (m)	Live crown (%)	Live crown length (m)	Live crown (%)	Live crown length (m)
T_0F_0	66	5.9	51	5.7	47	5.6	37	5.3
T_0F_1	70	6.3	59	7.1	54	6.9	42	6.8
T_0F_{1-1}	69	6.7	54	7.2	51	7.8	40	7.4
T_0F_2	69	5.5	61	7.2	52	6.7	38	6.0
T_0F_{2-2}	72	6.6	62	7.8	58	8.6	43	7.9
T_1F_0	73	7.3	62	7.6	58	7.8	45	7.2
T_1F_1	72	6.8	68	8.7	62	8.6	46	7.8
T_1F_{1-1}	75	8.0	62	8.5	58	8.9	46	8.6
T_1F_2	70	5.9	67	8.2	63	8.4	44	7.4
T_1F_{2-2}	72	7.4	63	9.0	56	8.9	41	8.2
T_2F_0	76	7.6	73	8.9	73	9.9	63	10.6
T_2F_1	77	8.2	76	10.8	74	11.8	58	11.4
T_2F_{1-1}	80	8.4	76	10.6	75	11.8	59	11.8
T_2F_2	75	7.3	78	11.0	74	11.5	54	10.5
T_2F_{2-2}	78	8.1	76	10.6	76	12.0	58	11.7

[1] Based on volume and extra height trees. Measurements were not taken at years 3 and 12.

Table 11a. Total volume (m^3/ha) by treatment and year

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T_0F_0	143	143	191	233	276	329	373
T_0F_1	124	124	184	239	286	342	387
T_0F_{1-1}	146	146	217	271	329	405	461
T_0F_2	92	92	158	222	275	334	386
T_0F_{2-2}	112	112	182	244	310	392	446
T_1F_0	131	88	122	159	206	255	300
T_1F_1	116	79	131	180	228	289	339
T_1F_{1-1}	142	95	155	203	260	336	405
T_1F_2	111	76	141	204	255	320	383
T_1F_{2-2}	161	101	176	247	322	421	490
T_2F_0	114	46	68	95	133	173	212
T_2F_1	130	49	90	132	185	240	290
T_2F_{1-1}	111	48	88	126	180	247	309
T_2F_2	100	45	95	150	201	261	319
T_2F_{2-2}	122	48	93	140	192	275	346

Table 11b. Net periodic annual volume increment (m^3/ha/yr) for each treatment combination

Treatment	Year							
	0-3	3-6	6-9	9-12	12-15	0-15	0-9	9-15
T_0F_0	16.0	14.0	14.3	17.7	14.7	15.3	14.8	16.2
T_0F_1	20.0	18.3	15.7	18.7	15.0	17.5	18.0	16.8
T_0F_{1-1}	23.7	18.0	19.3	25.3	18.7	21.0	20.3	22.0
T_0F_2	22.0	21.3	17.7	19.7	17.3	19.6	20.3	18.5
T_0F_{2-2}	23.3	20.7	22.0	27.3	18.0	22.3	22.0	22.7
T_1F_0	11.3	12.3	15.7	16.3	15.0	14.1	13.1	15.7
T_1F_1	17.3	16.3	16.0	20.3	16.7	17.3	16.6	18.5
T_1F_{1-1}	20.0	16.0	19.0	25.3	23.0	20.7	18.3	24.2
T_1F_2	21.7	21.0	17.0	21.7	21.0	20.5	19.9	21.3
T_1F_{2-2}	25.0	23.7	25.0	33.0	23.0	25.9	24.6	28.0
T_2F_0	7.3	9.0	12.7	13.3	13.0	11.1	9.7	13.2
T_2F_1	13.7	14.0	17.7	18.3	16.7	16.1	15.1	17.5
T_2F_{1-1}	13.3	12.7	18.0	22.3	20.7	17.4	14.7	21.5
T_2F_2	16.7	18.3	17.0	20.0	19.3	18.3	17.3	19.7
T_2F_{2-2}	15.0	15.7	17.3	27.7	23.7	19.9	16.0	25.7

(4) The F_2 plots had a greater total volume than the F_1 plots. Averaged over all thinning levels the F_2 plots had 13% (43 m^3/ha) more volume.

(5) The F_{1-1} plots had a greater total volume than the F_1 plots. Averaged over all thinning levels the F_{1-1} plots had 13% (45 m^3/ha) more volume.

(6) The F_{2-2} plots had a greater total volume than the F_2 plots. Averaged over all thinning levels the F_{2-2} plots had 10% (38 m^3/ha) more volume.

(7) The F_{2-2} plots had a greater total volume than the F_{1-1} plots. Averaged over all thinning levels, the F_{2-2} plots had 9% (36 m^3/ha) more volume.

(8) There was no difference in total volume between the F_{1-1} and F_2 plots.

The only treatments that had a significantly greater total volume than the control at year 15 were T_0F_{1-1}, T_0F_2, T_0F_{2-2}, and T_1F_{2-2}. The T_1F_0, T_2F_0, and T_2F_1 treatments still had significantly lower total volumes than the control 15 years after treatment. The remaining treatments did not differ significantly from the control.

Across all thinning levels, the plots fertilized only once were still adding total volume at a rate faster than that of the control plots (Table 11b). This prolonged response to fertilization is due in part to changes in stand structure and crown development caused by the treatment. In addition, because of their larger sizes, the trees in the fertilized plots will be adding a greater amount of volume each year than those in the unfertilized plots.

The greatest response to refertilization (F_1 *vs* F_{1-1}, and F_2 *vs* F_{2-2}) in terms of increased annual volume increment occurred in the heavily thinned stands. Periodic annual increments of the T_0F_2, T_0F_{2-2}, T_2F_2, and T_2F_{2-2} plots in the period from year 9 to year 15 were compared to their periodic annual increments in the first 9 years after treatment. The periodic annual increments of the T_2F_2 plots increased 2.4 m^3/ha/year after year 9, while the periodic annual increments in the T_2F_{2-2} plots increased 9.7 m^3/ha/year. In contrast, the average annual growth rate in the T_0F_2 plots decreased 1.8 m^3/ha/year after year 9,

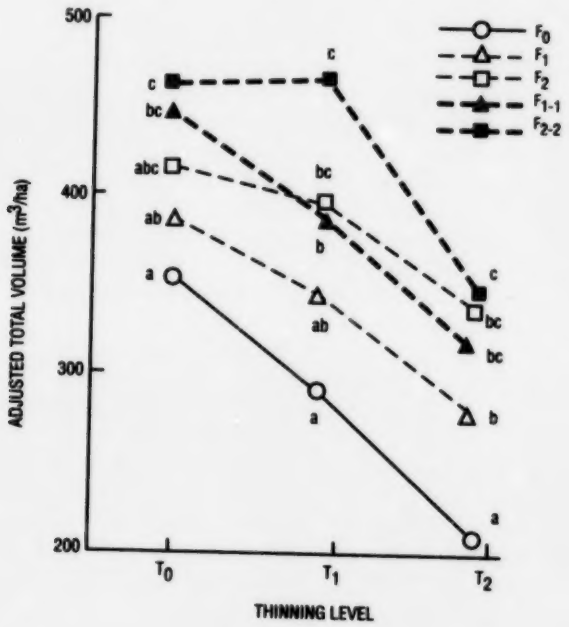


Figure 10. Adjusted total volume per hectare for each treatment combination 15 years after initial treatment. Total volume per hectare prior to treatment was used as the covariate to adjust volumes at year 15. Within each thinning level, volumes followed by the same letter are not significantly different ($p \leq 0.05$).

while the annual growth rate of the T_0F_{2-2} plots was increased by only 0.7 m^3/ha/year. In all treatments, net annual volume growth from year 12 to year 15 was less than that for years 9 through 12, but the refertilized plots continued to grow faster than those fertilized only once. Figure 11 illustrates the partitioning of total volume into individual stems by the number and average diameter of the stems.

How the total volume is partitioned among stems controls, to a large extent, the merchantable volume available, the value of the logs, and the harvesting costs. A given total volume will yield more merchantable volume if it is distributed among fewer stems of larger diameter. Subsequent sections of this report discuss the ranking of the treatments by merchantable volume.

4.6.2 Average individual stem volume

An analysis of covariance showed a significant interaction between thinning and fertilization on the average individual stem volume at 15 years (Appendix Table A11). Both thinning and fertilization increased individual stem volume. The response to refertilization varied among thinning levels, but was greatest in the T_2 plots. The adjusted individual stem volumes are presented in Appendix Table A16.

By removing one-third and two-thirds of the basal area (T_1 and T_2) the average stem volume over all fertilization levels at year 15 was increased by 37% (0.0551 m^3) and 129% (0.1914 m^3), respectively. The average tree in the T_2 plots was 67% (0.1363 m^3) larger than the average tree in the T_1 plots.

As the level of thinning increased, the response to additional fertilizer became more pronounced. The average tree in the T_0F_{2-2} plots had 60% (0.0886 m^3) more stem volume than the average tree in the T_0F_0 plots. The average tree in the T_2F_{2-2} plots had 70% (0.1697 m^3) more stem volume than the mean tree in the T_2F_0 plots.

The largest average stem volume at year 15 occurred in the T_2F_{2-2} plots, and was four times the average stem volume found in the control plots.

Average stem volume periodic annual increment (0 to 15 years) by initial 5-cm dbh classes is shown in Figure 12. The pattern of increasing annual growth rate with increasing initial size remained constant over all treatments. However, the smallest trees (those in the 5 to 10 cm initial dbh class) have benefited the most from both thinning and fertilization, with thinning having the greater impact. The greatest growth response in all three dbh classes occurred in the heavily thinned refertilized plots (T_2F_{2-2}), in which trees in the 5 to 10, 10 to 15, and 15 to 20 cm initial dbh classes grew six, three, and two times faster, respectively, than control trees of similar size.

4.6.3 Crop tree response

Similar to the analysis of covariance done for all trees per plot, analyses of total volume for both the 250 and 500 crop trees showed significant effects from both thinning and fertilization, without an interaction between the two treatments (Appendix Tables A12 and A13). Fertilization resulted in a significant increase in total volume. However, in contrast to the analyses done for all trees, thinning increased rather than decreased the total volume of crop trees. The adjusted total volumes for the 250 and 500 crop trees are shown in Figures 13a and 13b. Figure 14 compares the total volume of the core trees with those of the 250 and 500 crop trees.

4.6.4 Merchantable volume

Merchantable volume is calculated based on dbh limits of 12.5 and 17.5 cm [5], and is presented in Tables 12 and 13 with corresponding periodic annual increments.

Results of the analyses of covariance (Appendix Tables A14 and A15) showed that both thinning and fertilization had a significant effect on merchantable volume, without an interaction between treatments, for each of the two diameter limits. Adjusted merchantable volumes per hectare at year 15 for the two diameter limits are shown in Figures 15a and 15b.

12.5 cm diameter limit

When merchantable volumes were calculated with a dbh limit of 12.5 cm, the T_1F_{2-2} plots had the largest adjusted merchantable volume (310 m^3/ha), and the T_2F_0 plots had the least (150 m^3/ha). This represents a difference of 160 m^3/ha; the T_1F_{2-2} plots had over twice the volume of the $T2F_0$ plots. Only one treatment (T_2F_0) significantly lowered merchantable volume relative to the control. The T_0F_1, T_1F_0, T_1F_1, and T_2F_1 plots did not differ

5. Merchantable volumes presented in previous reports did not incorporate diameter limits (Barclay and Brix 1985a).

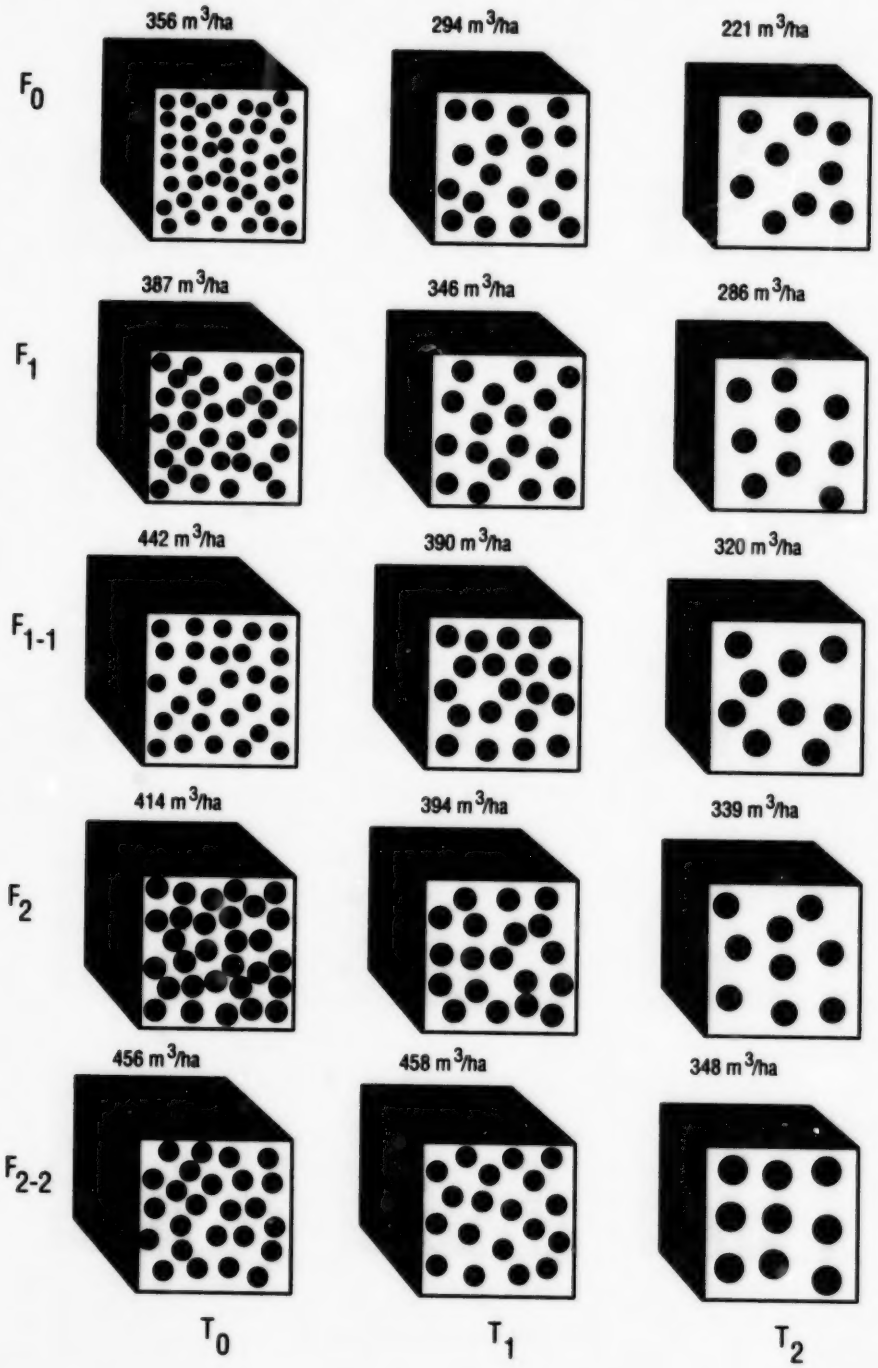


Figure 11. Adjusted total volume per hectare, quadratic mean diameter, and stems per hectare for each treatment combination 15 years after initial treatment. Dot size represents adjusted quadratic mean diameter; the number of dots represents the number of stems per hectare; and the volume of the boxes represents adjusted total volume. Adjusted total volumes for each treatment combination are given above each box.

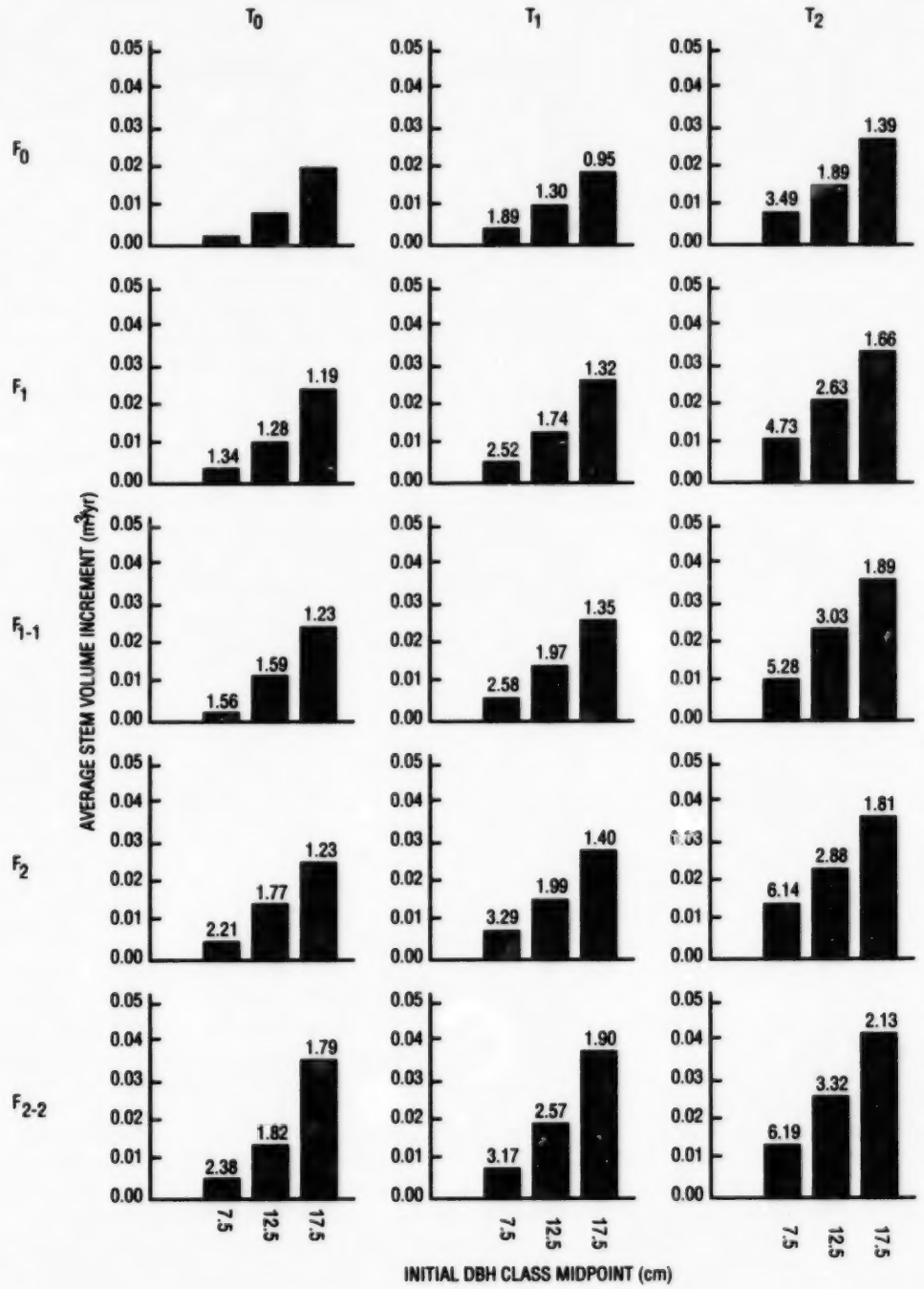


Figure 12. Average annual stem volume increments between year 0 and year 15 by 5-cm dbh classes for each treatment combination. Trees were placed into dbh classes based on their initial diameters at year 0. The numbers above the bars indicate the factor by which volume increment increased relative to trees of similar initial size in the control (T_0F_0) plot

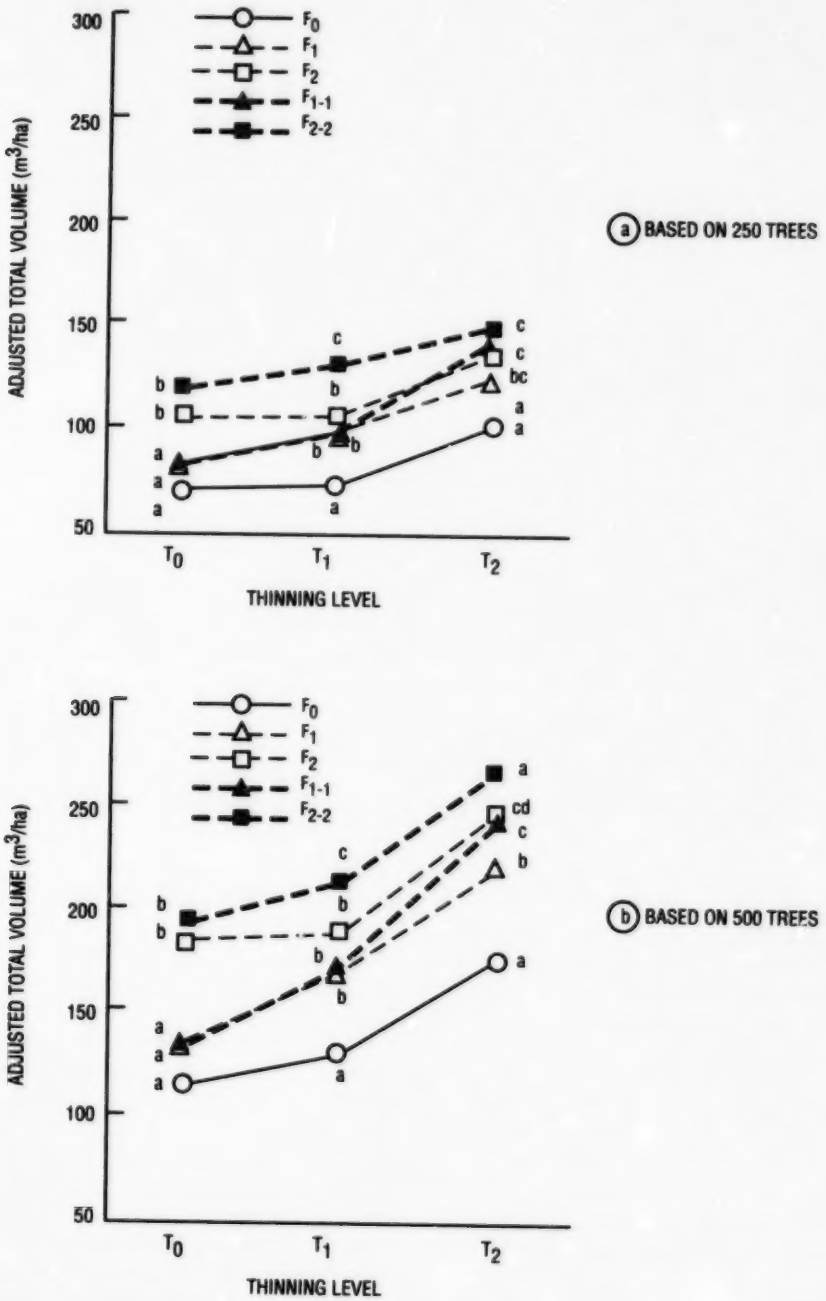


Figure 13. Adjusted total volume per hectare of the crop trees 15 years after initial treatment for each treatment combination. Initial total volumes of the crop trees were used as covariates to adjust the volumes at year 15. Within each thinning level, volumes followed by the same letter are not significantly different ($p \leq 0.05$).

(a) Based on 250 trees

(b) Based on 500 trees

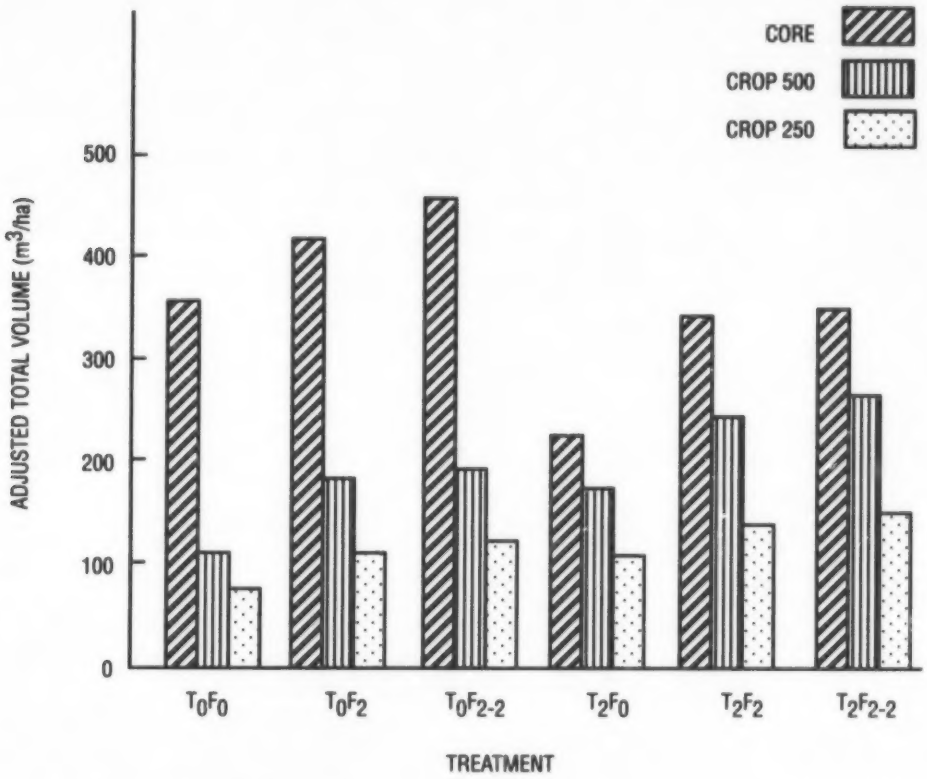


Figure 14. Adjusted total stand volume of core and crop trees for the six extreme treatments 15 years after initial treatment.

significantly from the control, while all other treatments had significantly more merchantable volume. In general, the following observations were made for the merchantable volume per hectare at year 15 with a 12.5-cm dbh limit:

(1) The greatest amount of merchantable volume occurred in the T_1 plots, followed by the T_0 plots and then the T_2 plots. No significant differences were found between the T1 and T_0 plots or the T_0 and T_2 plots; however, the T_1 plots had significantly more merchantable volume than the T_2 plots. Averaged across all fertilization levels the T_1 plots had 13% (28 m^3/ha) more merchantable volume than the T_2 plots.

(2) All levels of fertilization resulted in greater merchantable volumes than the unfertilized plots. Averaged over all thinning levels, merchantable volumes increased over that in unfertilized plots as follows: F_1 20% (35 m^3/ha); F_{1-1} 44% (75 m^3/ha); F_2 43% (73 m^3/ha); and F_{2-2} 65% (111 m^3/ha).

(3) The F_2 plots had a greater merchantable volume than the F_1 plots. Averaged over all thinning levels, the F_2 plots had 18% (38 m^3/ha) more merchantable volume.

(4) The merchantable volume of the refertilized plots exceeded that of those plots fertilized only once. Averaged over all thinning levels the F_{1-1} plots had 19% (40 m^3/ha) more merchantable volume than the F1 plots and the F_{2-2} plots had 16% (38 m^3/ha) more merchantable volume than the F_2 plots.

(5) The F_{2-2} plots had a greater merchantable volume than the F_{1-1} plots. Averaged over all thinning levels the F_{2-2} plots had 15% (36 m^3/ha) more merchantable volume.

(6) There was no difference in merchantable volume response to 448 kg N/ha whether applied in one dose (F_2) or two doses (F_{1-1}).

17.5 cm diameter limit

When merchantable volumes were calculated with a dbh limit of 17.5 cm, the largest adjusted merchantable volume occurred in the T_2F_{2-2} plots

Table 12a. Merchantable volume (m^3/ha) by treatment and year based on a dbh limit of 12.5 cm [1]

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T_0F_0	17	17	39	65	95	132	170
T_0F_1	22	22	53	92	125	174	214
T_0F_{1-1}	33	33	77	119	161	226	280
T_0F_2	4	4	31	72	113	166	211
T_0F_{2-2}	16	16	56	107	162	235	287
T_1F_0	19	16	38	66	100	138	176
T_1F_1	17	12	48	87	124	176	216
T_1F_{1-1}	30	23	65	103	148	213	269
T_1F_2	11	9	49	104	148	199	248
T_1F_{2-2}	40	18	71	131	190	271	334
T_2F_0	19	9	26	49	81	116	147
T_2F_1	19	7	45	80	121	167	208
T_2F_{1-1}	11	9	43	79	121	175	225
T_2F_2	10	9	48	98	140	188	234
T_2F_{2-2}	19	10	51	90	133	200	256

Table 12b. Periodic annual merchantable volume increments (m^3/ha/yr) for each treatment combination based on a dbh limit of 12.5 cm

Treatment	Year							
	0-3	3-6	6-9	9-12	12-15	0-15	0-9	9-15
T_0F_0	7.3	8.7	10.0	12.3	12.7	10.2	8.7	12.5
T_0F_1	10.3	13.0	11.0	16.3	13.3	12.8	11.4	14.8
T_0F1-1	14.7	14.0	14.0	21.7	18.0	16.5	14.2	19.8
T_0F_2	9.0	13.7	13.7	17.7	15.0	13.8	12.1	16.3
T_0F_{2-2}	13.3	17.0	18.3	24.3	17.3	18.1	16.2	20.8
T_1F_0	7.3	9.3	11.3	12.7	12.7	10.7	9.3	12.7
T_1F_1	12.0	13.0	12.3	17.3	13.3	13.6	12.4	15.3
T_1F_{1-1}	14.0	12.7	15.0	21.7	18.7	16.4	13.9	20.2
T_1F_2	13.3	18.3	14.7	17.0	16.3	15.9	15.4	16.7
T_1F_{2-2}	17.7	20.0	19.7	27.0	21.0	21.1	19.1	24.0
T_2F_0	5.7	7.7	10.7	11.7	10.3	9.2	8.0	11.0
T_2F_1	12.7	11.7	13.7	15.3	13.7	13.4	12.7	14.5
T_2F_{1-1}	11.3	12.0	14.0	18.0	16.7	14.4	12.4	17.3
T_2F_2	13.0	16.7	14.0	16.0	15.3	15.0	14.6	15.7
T_2F_2	13.7	13.0	14.3	22.3	18.7	16.4	13.7	20.5

[1] 10 cm top diameter, 30-cm stump

Table 13a. Merchantable volume (m^3/ha) by treatment and year based on a dbh limit of 17.5 cm [1]

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T_0F_0	5	5	9	15	28	46	71
T_0F_1	6	6	16	39	55	86	122
T_0F_{1-1}	16	16	32	53	81	150	206
T_0F_2	0	0	2	11	30	79	114
T_0F_{2-2}	0	0	17	37	74	152	208
T_1F_0	4	2	9	15	38	70	101
T_1F_1	0	0	13	24	59	111	160
T_1F_{1-1}	4	4	15	38	87	148	207
T_1F_2	3	2	7	27	77	129	181
T_1F_{2-2}	10	2	19	59	117	207	272
T_2F_0	6	2	6	18	41	78	112
T_2F_1	0	0	8	39	89	138	186
T_2F_{1-1}	2	2	13	39	80	146	208
T_2F_22	0	0	15	58	110	168	221
T_2F_{2-2}	1	1	13	59	113	185	244

Table 13b. Periodic annual merchantable volume increments (m^3/ha/yr) for each treatment combination based on a dbh limit of 17.5 cm

Treatment	Year							
	0-3	3-6	6-9	9-12	12-15	0-15	0-9	9-15
T_0F_0	1.3	2.0	4.3	6.0	8.3	4.4	2.6	7.2
T_0F_1	3.3	4.7	8.3	10.3	12.0	7.7	5.4	11.2
T_0F_{1-1}	5.3	7.0	9.3	23.0	18.7	12.7	7.2	20.8
T_0F_2	0.7	3.0	6.3	16.3	11.7	7.6	3.3	14.0
T_0F_{2-2}	5.7	6.7	12.3	26.0	18.7	13.9	8.2	22.3
T_1F_0	2.3	2.0	7.7	10.7	10.3	6.6	4.0	10.5
T_1F_1	4.3	3.7	11.7	17.3	16.3	10.7	6.6	16.8
T_1F_1	3.7	7.7	16.3	20.3	19.7	13.5	9.2	20.0
T_1F_2	1.7	6.7	16.7	17.3	17.3	11.9	8.3	17.3
T_1F_{2-2}	5.7	13.3	19.3	30.0	21.7	18.0	12.8	25.8
T_2F_0	1.3	4.0	7.7	12.3	11.3	7.3	4.3	11.8
T_2F_1	2.7	10.3	16.7	16.3	16.0	12.4	9.9	16.2
T_2F_{1-1}	3.7	8.7	13.7	22.0	20.7	13.7	8.7	21.3
T_2F_2	5.0	14.3	17.3	19.3	17.7	14.7	12.2	18.5
T_2F_{2-2}	4.0	15.3	18.0	24.0	19.7	16.2	12.4	21.8

[1] 10 cm top diameter, 30-cm stump

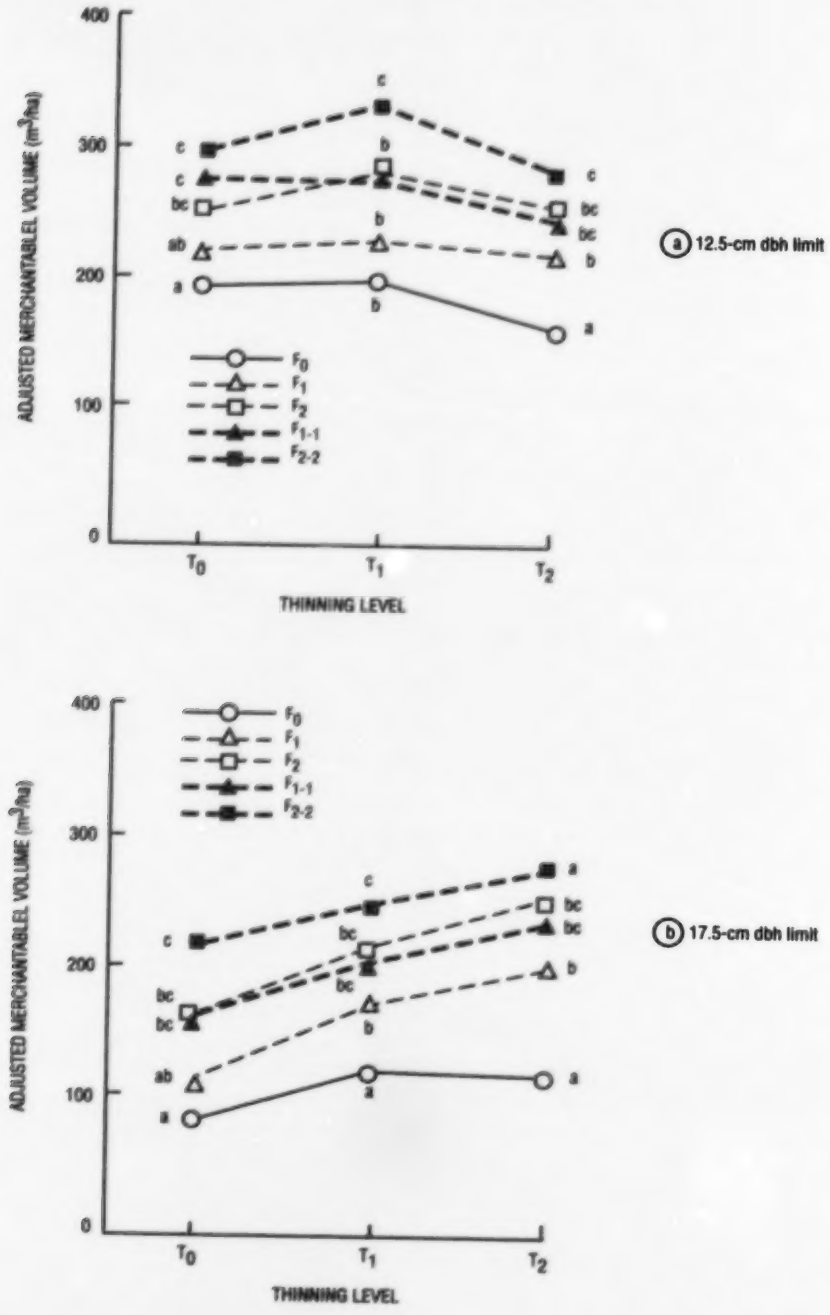


Figure 15. Adjusted merchantable volume per hectare 15 years after initial treatment for each treatment combination. Within each thinning level, volumes followed by the same letter are not significantly different ($p \leq 0.05$).

(a) 12.5-cm dbh limit. The average basal area per tree prior to treatment was used as the covariate to adjust merchantable volumes at year 15.

(b) 17.5-cm dbh limit. The average basal area per tree and total merchantable volume prior to treatment were used as covariates to adjust merchantable volumes at year 15.

(257 m^3/ha); these plots had over three times the adjusted merchantable volume of the control plots, which had the lowest amount (81 m^3/ha). The T_0F_1, T_1F_0, and T_2F_0 plots did not differ significantly from the control plots, while all other treatments had significantly more merchantable volume at a 17.5-cm dbh limit at year 15. The following observations were made for the gross merchantable volume per hectare at year 15 with a 17.5-cm dbh limit:

(1) Thinning increased the merchantable volume. Averaged over all fertilization levels the T_1 plots had 29% (40 m^3/ha) more merchantable volume than the T_0 plots and the T_2 plots had 13% (23 m^3/ha) more than the T_1 plots and 46% (63 m^3/ha) more than the T_0 plots.

(2) Fertilization increased the merchantable volume. Averaged over all thinning levels, merchantable volumes increased over the unfertilized plots as follows: F_1 49% (50 m^3/ha); $F_{1\text{-}1}$ 91% (93 m3/ha); F_2 81% (83 m^3/ha); and $F_{2\text{-}2}$ 124% (126 m^3/ha).

(3) The F_2 plots had a greater merchantable volume than the F_1 plots. Averaged over all thinning levels the F_2 plots had 22% (33 m^3/ha) more merchantable volume.

(4) The merchantable volume of the refertilized plots exceeded that of plots only fertilized once. Averaged over all thinning levels the $F_{1\text{-}1}$ plots had 28% (43 m^3/ha) more merchantable volume than the F_1 plots and the $F_{2\text{-}2}$ plots had 23% (43 m^3/ha) more merchantable volume than the F_2 plots.

(5) The $F_{2\text{-}2}$ plots had a greater merchantable volume than the $F_{1\text{-}1}$ plots. Averaged over all thinning levels the $F_{2\text{-}2}$ plots had 17% (33 m^3/ha) more merchantable volume.

(6) There was no difference in merchantable volume response to 448 kg N/ha whether applied in one dose (F_2) or two doses ($F_{1\text{-}1}$).

5. Discussion

Many studies have characterized the effects of thinning and fertilization on the growth of coastal Douglas-fir. Response to these treatments has been variable; hence, the main objective of the Shawnigan Lake project has been to provide a better understanding of the processes and conditions in the soil, atmosphere, and trees which play critical roles in the growth response to these treatments.

Information presented in this report serves two purposes: first, it provides a baseline of mensurational information for other studies within the project; second, it provides specific information on the growth response of young Douglas-fir to thinning and fertilization on a poor site with dense initial stocking. In view of the poor site quality, the response to fertilization is expected to be high, and the response to thinning will likely be strongly influenced by the water and nutrient deficits on the site.

The importance of thinking of stand tending practices in terms of crown manipulation has been stressed by H. Brix.[6] The changes in individual tree crown development brought about by thinning and fertilization, combined with the amount of available growing space occupied by these crowns over time, strongly influence the stand response to treatments.

Thinning results in improved light availability to the crowns, and, particularly on drier sites, improved water availability. These improvements encourage the retention of longer crowns with a greater needle mass (Brix 1981a). This in turn increases carbohydrate production necessary for growth.

Urea fertilization affects the crown in two ways. Initially, urea fertilization increases the nitrogen content of the foliage. This improved nutrition is associated with an increase in the photosynthetic rate (Brix 1981b). An increased photosynthetic rate results in a greater production of carbohydrates which leads not only to greater stem growth but also to increased production of needles. This gain in foliage is the second component of the response to urea fertilization. Therefore, the crown responses to urea fertilization are initially due to gains in photosynthetic efficiency and subsequently due to gains in the amount of foliage, both of which result in the increased production of carbohydrates required for growth (Brix 1983).

5.1 Influence of initial stand conditions

For all tree or stand attributes measured, with the exception of top height, one or two covariates specifying the initial stand conditions proved to be significant in analyses of treatment effects. This confirms that initial stand conditions affect the observed response to the treatments.

In previous reports, data for the 1971 and 1972 plots were not separated prior to year 9, which meant that the growth of the two sets of plots after year 9

6. Research Scientist, retired, Pacific Forestry Centre, Victoria, British Columbia, Personal communication 1988.

was compared to the combined average growth preceding year 9. On average, the 1972 plots (having been established 1 year later) had more volume at year 0 than the 1971 plots and therefore, the response to refertilization presented in the 12-year report (Barclay and Brix 1985a) was slightly exaggerated.

5.2 Thinning

Fifteen years after initial treatment, the heavily thinned plots had the largest individual tree sizes, but still contained less total volume per hectare than the moderately thinned or unthinned plots. Ranking of total volume per hectare was $T_0 > T_1 > T_2$, while ranking of average individual tree size was $T_2 > T_1 > T_0$.

The economic benefit of average tree size was evident when the ranking for merchantable volume was examined. At a dbh limit of 12.5 cm the ranking was $T_1 > T_0 > T_2$, while at a dbh limit of 17.5 cm the ranking was $T_2 > T_1 > T_0$. In addition, heavier thinning resulted in a more uniform stand, both in terms of diameter and height distribution. This latter benefit is important when the objective is sawlog production, as a more uniform piece size results in lower harvesting and manufacturing costs.

As shown in previous years, the largest trees in all treatments had the greatest periodic annual diameter and stem volume increments during the period from 0 to 15 years. The smallest trees benefited the most from thinning in terms of increased growth rates, compared to trees of similar initial size in the unthinned plots. Small trees in the control plots remained suppressed and died sooner, while small trees in the thinned plots, which were less affected by competition, were better able to survive.

Previous studies have found that the height growth of dominant trees is independent of density (Braathe 1957). However, for the top height trees at Shawnigan Lake, height growth tended to increase as stand density decreased. With the first 3-year period excluded so that the effect of thinning shock (Crown et al. 1977) was removed, the average annual growth rate of the top height trees from year 3 to year 9 was significantly increased by thinning. This positive effect of thinning may be due to an increase in water availability. Brix and Mitchell (1986) found that thinning increased the soil water potential during the dry summer months both with and without fertilization. In addition, increased moisture availability in the thinned plots may result in an improved nutrient status, particularly on this poor site (Brix 1979).

5.3 Fertilization

Fertilization increased the total and merchantable volume per hectare, and increasing amounts of fertilizer resulted in greater volume. Response to fertilization on an individual tree basis varied among thinning levels, with the largest growth increases occurring in the heavily thinned plots. If the response to fertilization is due to both an increase in foliar efficiency and foliar mass, the trees in the heavily thinned plots would tend to show the best response, as they had the most space in which to expand their crowns.

Fertilization substantially accelerated mortality in the unthinned plots by escalating the suppression of smaller trees. This must be considered when examining average tree size over time as part of the increase in average size is due to the removal of the smaller stems.

Across all thinning levels, the net annual volume increments from year 12 to year 15 of plots fertilized only once with either 224 or 448 kg N/ha continued to exceed those of unfertilized plots. This prolonged growth response is due to changes in stand and crown structure, brought about by fertilization.

5.4 Refertilization

Across all thinning levels, refertilization resulted in substantial increases in diameter, height, and total volume increments for the first 3 years (years 9-12) after refertilization. At year 15, the refertilized plots continued to grow faster than those fertilized only once.

The duration of response to refertilization appears to be correlated to the space available for crown expansion. In the unthinned (T_0) and moderately thinned (T_1) plots fertilized with 448 kg N/ha, crown closure had occurred before the second application of fertilizer. This is reflected by lower growth rates in the second 3-year period (years 12-15) after refertilization than those prior to refertilization (years 6-9). By contrast, crown closure in the heavily thinned (T_2) plots had not yet occurred, and, subsequently, the growth rates in the second 3-year period remained higher than those prior to refertilization. Therefore, the response to a second application of fertilizer in unthinned and moderately thinned stands may be limited to only short-lived increases in foliar efficiency, rather than to more prolonged responses occurring in heavily thinned stands, where trees have room to expand their crowns.

To year 15, there have been no measurable differences in the response to one application of 448 kg N/ha (F_2) as compared to two applications of 224 kg N/ha (F_{1-1}).

5.5 Thinning vs Fertilization

Average diameters of the crop trees did not differ between unthinned fertilized plots and thinned unfertilized plots. This raises the question of whether to use fertilizer alone instead of thinning alone to promote the growth of crop trees, especially when fertlizer is the less expensive treatment. Fertilization alone may be an option on poorer quality sites such as Shawnigan Lake, where the lack of nutrients limits the response to thinning but results in a beneficial fertilization response. The response to fertilization alone will also depend on the stand structure at the time of application. If the stand is well differentiated, the dominant trees will be better able to make use of the fertilizer, with losses to mortality occurring in the small suppressed trees. In a study of crop tree response to fertilization in unspaced Douglas-fir stands, Carter (1989) concluded that such stands should only be fertilized if they contain well established dominants. Within the Shawnigan Lake project, a large biomass study which commenced in the fall of 1988 includes the collection of information on crown structure and development. Differences in crown development between the largest trees of the T_2F_0 plots and the T_0F_2 plots will be compared, and this should provide insight into how these trees will grow and how they would respond to further stand tending activities.

6. Conclusions

(1) Thinning increased the average individual tree size but decreased total volume per hectare. Fifteen years after treatment, the ranking for individual tree size was $T_2 > T_1 > T_0$ and the ranking for total volume per hectare was the reverse. However, based on merchantable volume per hectare at a dbh limit of 17.5 cm, the ranking after 15 years was similar to that for individual tree size.

(2) Fertilization increased both the total and merchantable volumes per hectare, and increasing amounts of fertilizer resulted in additional volume. Response to fertilization on an individual tree basis varied among the thinning levels, with the greatest increases in growth occurring in the heavily thinned plots.

(3) The largest average individual stem volume at year 15 was in the T_2F_{2-2} plots, where average stem volume was four times that in the control plots.

(4) The plots having a greater total volume than the control plots were the T_0F_{1-1}, T_0F_2, T_0F_{2-2}, and T_1F_{2-2} plots. The T_1F_0, T_2F_0, and T_2F_1 plots still had significantly lower total volumes per hectare than the control plots.

(5) With the exception of the T_1F_0, T_2F_0, and T_0F_1 plots, all plots had more merchantable volume at a dbh limit of 17.5 than the control plots.

(6) Across all thinning levels, plots fertilized once with either 224 or 448 kg N/ha continued to have net annual volume increments greater than those in unfertilized plots 15 years after fertilization.

(7) Up to year 15, there have been no measurable differences between the response to one application of 448 kg N/ha and that to two applications of 224 kg N/ha.

(8) The volume response to a second application of fertilizer was greatest in the heavily thinned plots. In these plots, an increased volume response (compared to plots that were fertilized only once) was still evident during the period from year 12 to year 15. In the unthinned plots, the volume response to refertilization was limited to the first 3 to 4 years after application.

(9) Thinning did not have a significant effect on average annual top height growth for the first 9 years after treatment. However, thinning shock reduced growth for the first 3 years. With this period omitted, thinning significantly increased the average annual top height growth for the period from year 3 to year 9. Fertilization significantly increased average annual top height growth in the first 9 years after treatment.

(10) Thinning alone increased quadratic mean diameter much more than fertilization alone. However, both treatments resulted in similar average diameters of the 250 and 500 crop trees per hectare.

(11) The largest trees in all treatments had the greatest periodic annual diameter and stem volume increments during the first 15 years after treatment.

However, the smallest trees benefited the most from thinning in terms of increased growth rates, compared with trees of similar size in the control plots. For example, in the T_2F_{2-2} plots, trees initially in the 5-10 cm diameter class added stem volume six times faster than control trees of similar size.

(12) In the first 15 years after treatment, most mortality occurred in the unthinned plots, and within these plots fertilization accelerated mortality.

Literature cited

Barclay, H.J.; Brix, H. 1984. Effects of urea and ammonium nitrate fertilizer on the growth of a young thinned and unthinned Douglas-fir stand. Can. J. For. Res. 14(6):952-955.

Barclay, H.J.; Brix, H. 1985a. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 12 year growth response. Can. For. Serv., Pac. For. Cent. Inf. Rep. BC-X-271, 34 p.

Barclay, H.J.; Brix, H. 1985b. Effects of high levels of fertilization with urea on the growth of thinned and unthinned Douglas-fir stands. Can. J. For. Res. 15(4):730-733.

Barclay, H.J.; Brix, H.; Layton, C.R. 1982. Fertilization and thinning effects on a Douglas-fir ecosystem: 9 year growth response. Can. For. Serv. Pac. For. Res. Cent. Inf. Rep. BC-X-238, 35 p.

Braathe, P. 1957. Thinnings in even-aged stands a summary of European literature. Univ. New Brunswick, Fac. For. 92 p.

British Columbia Forest Service. 1976. Whole stem cubic metre volume equations and tables. Centimetre diameter class merchantable volume factors. B.C. For. Serv., Victoria, B.C.

British Columbia Forest Service. 1989. Intensive Management Guidelines - Coastal. B.C. For. Serv., Vancouver Region. Pg. 7-9.

Brix, H. 1979. Moisture - nutrient interrelationships. In: Forest Fertilization Conference. Univ. Wash. Inst. For. Res. Contrib. No. 40.

Brix, H. 1981a. Effects of thinning and nitrogen fertilization on branch and foliage production in Douglas-fir. Can. J. For. Res. 11:502-511.

Brix, H. 1981b. Effects of nitrogen fertilizer source and application rates on foliar nitrogen concentration, photosynthesis, and growth of Douglas-fir. Can. J. For. Res. 11:775-780

Brix, H. 1983. Effects of thinning and nitrogen fertilization on growth of Douglas-fir: relative contribution of foliage quantity and efficiency. Can. J. For. Res. 13:167-175.

Brix, H.; Mitchell, A.K. 1986. Thinning and nitrogen fertilizer effects on soil and tree water stress in a Douglas-fir stand. Can. J. For. Res. 16:1334-1338.

Browne, J.E. 1962. Standard cubic-foot volume tables for the commercial tree species of B.C., B.C. For. Serv., Forest Surveys and Inventory Div., 107 p.

Bruce, D. 1981. Consistent height-growth and growth-rate estimates for remeasured plots. For. Sci. 27(4):711-725.

Carter, R. 1989. Variability of crop tree response to fertilization in unspaced Douglas -fir stands. FRDA Rep. 085,18p.

Crown, M.; Brett, C.P. 1975. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: an establishment report. Can. For. Serv., Pac. For. Res. Cent. Inf. Rep. BC-X-110, 45 p.

Crown, M.; Quenet. R.V.; Layton, C.R. 1977. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 3-year growth response. Can. For. Serv. Pac. For. Res. Cent. Inf. Rep. BC-X-152, 36 p.

Freund, R.J.; Littell, R.C.; Spector, P.C. 1986. SAS System for Linear Models. SAS Institute Inc. Cary, N.C. 210 p.

Hall, T.H.; Quenet, R.V.; Layton, C.R.; Robertson, R.J. 1980. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 6-year growth response. Can. For. Serv. Pac. For. Res. Cent. Inf. Rep. BC-X-202, 31 p.

Husch, B.; Miller, C.I.; Beers, T.W. 1982. Forest Mensuration. 3rd ed., Wiley, New York.

Klinka, K.; Green, R.N.; Courtin, P.J.; Nuszdorfer, F.C. 1984. Site diagnosis, tree species selection, and slashburning guidelines for the Vancouver forest region. B.C. For. Serv. Land Manage. Rep. No. 25. 180 p.

Miller, D.M. 1984. Reducing transformation bias in curve fitting. Am. Statistician 38(2):124-126.

Omule, S.A.Y.; Fletcher, V.E.; Polsson. K.R. 1987. Total and merchantable volume equations for small coastal Douglas-fir. FRDA Rep. 010, 16 p.

SAS Institute Inc. 1985. Sas Users Guide: Statistics, Version 5 Edition. SAS Institute Inc. Cary, N.C. 956 p.

Snedecor,G.W.; Cochran,W.G. 1967. Statistical Methods. 6th edition. Iowa State University Press. Ames, Iowa. 593 p.

Appendices

Table A1. Volume equation coefficients by treatment for individual tree volumes 12 years after treatment. The equation used was vol increment = $a + b \cdot (BA) + c \cdot$(ba increment).

Year of treatment	Treatment	Number of trees	Regression Coefficients				
			a	*b*	*c*	R^2	SEE
1971	T_0F_0	28	-0.0056	1.6590	4.4152	0.9927	0.0036
	T_0F_1	19	-0.0058	0.9141	8.0519	0.9911	0.0037
	T_0F_2	15	-0.0048	1.4681	4.7842	0.9959	0.0015
	T_1F_0	39	-0.0030	0.8690	7.4322	0.9841	0.0036
	T_1F_1	30	-0.0073	1.3190	6.8571	0.9604	0.0068
	T_1F_2	20	-0.0017	0.9799	6.4818	0.9694	0.0039
	T_2F_0	11	-0.0092	-0.1738	13.9098	0.9619	0.0038
	T_2F_1	18	-0.0042	0.8698	8.9094	0.9776	0.0059
	T_2F_2	18	-0.0048	1.3967	5.6720	0.9551	0.0078
1972	T_0F_0	26	-0.0002	-0.0787	11.4726	0.9857	0.0019
	$T_0F_{1\text{-}1}$	20	-0.0051	0.5345	11.4613	0.9946	0.0046
	$T_0F_{2\text{-}2}$	20	-0.0071	0.9625	8.6712	0.9866	0.0059
	T_1F_0	28	-0.0019	0.8510	6.2623	0.9640	0.0043
	$T_1F_{1\text{-}1}$	25	-0.0069	0.2779	12.7069	0.9574	0.0087
	$T_1F_{2\text{-}2}$	23	-0.0095	1.2806	9.5760	0.9730	0.0083
	T_2F_0	20	-0.0107	1.8205	4.7462	0.9690	0.0049
	$T_2F_{1\text{-}1}$	14	-0.0092	0.1641	13.0773	0.9377	0.0108
	$T_2F_{2\text{-}2}$	18	-0.0141	1.5865	8.4055	0.9890	0.0059

Table A2. Volume equation coefficients by treatment for individual tree volumes 15 years after treatment. The equation used was vol increment = $a + b\cdot(BA) + c\cdot$(ba increment).

Year of treatment	Treatment	Number of trees	Regression Coefficients				
			a	*b*	*c*	R^2	SEE
1971	T_0F_0	25	-0.0088	1.8049	9.0117	0.9958	0.0055
	T_0F_1	17	-0.0135	1.7579	8.7730	0.9945	0.0056
	T_0F_2	12	-0.0091	2.3802	6.8396	0.9873	0.0051
	T_1F_0	39	-0.0075	1.6899	8.6721	0.9887	0.0062
	T_1F_1	30	-0.0121	1.6444	10.0026	0.9755	0.0107
	T_1F_2	20	-0.0047	1.9117	7.4941	0.9598	0.0093
	T_2F_0	11	-0.0060	0.1194	11.6734	0.9698	0.0067
	T_2F_1	17	-0.0167	2.1039	9.4016	0.9864	0.0096
	T_2F_2	18	-0.0218	1.3733	11.2179	0.9708	0.0134
1972	T_0F_0	24	-0.0012	0.0448	11.0786	0.9948	0.0022
	$T_0F_{1\text{-}1}$	20	-0.0090	0.4692	13.9298	0.9934	0.0094
	$T_0F_{2\text{-}2}$	18	-0.0127	0.8315	11.8868	0.9876	0.0113
	$T1F_0$	27	-0.0059	1.3626	8.2118	0.9841	0.0058
	$T1F_{1\text{-}1}$	24	-0.0144	1.0020	12.7657	0.9778	0.0126
	$T1F_{2\text{-}2}$	22	-0.0224	2.5127	10.1772	0.9782	0.0140
	T_2F_0	20	-0.0217	4.0843	4.0695	0.9731	0.0093
	$T_2F_{1\text{-}1}$	13	-0.0372	1.3577	13.8049	0.9605	0.0185
	$T_2F_{2\text{-}2}$	17	-0.0286	3.0210	9.1614	0.9921	0.0097

Table A3. Analysis of covariance on quadratic mean diameters (Dbhq) 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	17	22.243	111.49	0.0001	0.9906
Initial Dbhq	1	21.041	105.46	0.0001	
Initial Dbhq*Thinning	2	1.105	5.54	0.0133	
Thinning	2	3.021	15.14	0.0001	
Fertilization	4	14.381	72.08	0.0001	
Thinning*Fertilization	8	0.635	3.18	0.0197	
Error	18	0.200			

Table A4. Analysis of covariance on diameters of 250 crop trees per hectare 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	36	117.233	69.90	0.0	0.8862
Initial Dbh	1	2231.543	553.40	0.0001	
Thinning	2	365.109	90.54	0.0001	
Fertilization	4	193.974	48.10	0.0001	
Thinning*Fertilization	8	4.854	0.60	0.7659	
Error	21	4.032			

Table A5. Analysis of covariance on diameters of 500 crop trees per hectare 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	36	224.964	131.41	0.0	0.8738
Initial Dbh	1	4778.605	981.41	0.0001	
Thinning	2	906.498	186.17	0.0001	
Fertilization	4	368.396	75.66	0.0001	
Thinning*Fertilization	8	3.905	0.80	0.6079	
Error	21	4.869			

Table A6. Analysis of covariance on total basal area 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	160.735	21.01	0.0001	0.9403
(Initial Total BA) * (Average BA per tree)	1	35.974	4.70	0.0424	
Thinning	2	664.474	86.85	0.0001	
Fertilization	4	92.423	12.08	0.000	
Thinning*Fertilization	8	27.013	1.77	0.1443	
Error	20	7.651			

Table A7. Analysis of covariance on average heights 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	11.424	9.96	0.0001	0.8820
Pre-treatment average height	1	14.168	12.35	0.0022	
Thinning	2	26.084	22.75	0.0001	
Fertilization	4	15.367	13.40	0.0001	
Thinning*Fertilization	8	1.078	0.47	0.8628	
Error	20	1.147			

Table A8. Analysis of variance on annual height increments of the top height trees for the first nine years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	35	0.032	11.33	0.0001	0.7860
Thinning	2	0.025	2.48	0.1026	
Fertilization	2	0.398	39.86	0.0001	
Thinning*Fertilization	4	0.001	0.11	0.9775	
Error	27	0.010			

Table A9. Analysis of variance on annual height increments of the top height trees from year 3 to year 9

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	35	0.027	9.00	0.0001	0.7448
Thinning	2	0.077	6.11	0.0065	
Fertilization	2	0.211	16.71	0.0001	
Thinning*Fertilization	4	0.002	0.20	0.9338	
Error	27	0.013			

Table A10. Analysis of covariance on total volume 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	13389.5	16.35	0.0001	0.9246
Initial Total Volume	1	5033.6	6.15	0.0222	
Thinning	2	31301.7	38.23	0.0001	
Fertilization	4	21298.2	26.01	0.0001	
Thinning*Fertilization	8	468.0	0.57	0.7888	
Error	20	818.8			

Table A11. Analysis of covariance on individual tree volumes 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	0.02057	120.93	0.0001	0.9891
Initial Average Volume	1	0.02332	137.07	0.0001	
Thinning	2	0.10510	617.73	0.0001	
Fertilization	4	0.01496	87.93	0.0001	
Thinning*Fertilization	8	0.00125	7.36	0.0001	
Error	20	0.00017			

Table A12. Analysis of covariance on total volume (m^3/ha) of 250 crop trees per hectare 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	1608.871	29.49	0.0001	0.9567
Initial Volume	1	6109.067	111.98	0.0001	
Thinning	2	3169.238	58.09	0.0001	
Fertilization	4	2884.259	52.87	0.0001	
Thinning*Fertilization	8	87.455	1.60	0.1864	
Error	20	54.557			

Table A13. Analysis of covariance on total volume (m^3/ha) of 500 crop trees per hectare 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	4478.1157	43.66	0.0001	0.9704
Initial Volume	1	13495.245	131.58	0.0001	
Thinning	2	11644.763	113.54	0.0001	
Fertilization	4	8740.564	85.22	0.0001	
Thinning*Fertilization	8	231.751	2.26	0.0666	
Error	20	102.559			

Table A14. Analysis of covariance on merchantable volume (m^3/ha) with a dbh limit of 12.5 cm 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	6690.886	16.98	0.0001	0.9272
Initial average BA per tree	1	9975.906	25.31	0.0001	
Thinning	2	2122.251	5.38	0.0135	
Fertilization	4	14060.292	35.68	0.0001	
Thinning*Fertilization	8	253.302	0.64	0.7334	
Error	20	394.117			

Table A15. Analysis of covariance on merchantable volume (m^3/ha) with a dbh limit of 17.5 cm 15 years after treatment

Source	DF	Mean Square	F Value	Prob > F	R-Square
Model	15	9452.411	19.15	0.0001	0.9416
Initial average BA per tree	1	16008.622	32.43	0.0001	
Initial merch vol	1	3673.128	7.44	0.0134	
Thinning	2	10575.769	21.43	0.0001	
Fertilization	4	18754.038	38.00	0.0001	
Thinning*Fertilization	8	356.405	0.72	0.6705	
Error	20	493.564			

Table A16. Adjusted means from analyses of covariance 15 years after treatment

Treatment	Quadratic Mean Diameter			Average Height	Basal Area	Total Volume			Merch. v.olume		Individual tree vol
	Core Trees	Crop 250	Crop 500			Core Trees	Crop 250	Crop 500	12.5-cm Limit	17.5-cm Limit	Core Trees
	cm			(m)	(m^2/ha)	m^3/ha			m^3/ha		(m^3)
T_0F_0	12.6	20.3	18.3	13.3	46.1	356	72	113	179	81	0.1006
T_0F_1	13.2	21.6	19.5	15.6	46.2	387	82	131	205	107	0.1182
T_0F_{1-1}	14.4	21.8	19.9	17.0	48.9	442	83	133	257	150	0.1502
T_0F_2	16.3	23.1	21.2	16.7	46.3	414	107	183	234	153	0.1839
T_0F_{2-2}	16.0	24.1	22.0	17.6	50.8	456	119	192	275	201	0.1892
T_1F_0	15.6	20.9	19.3	15.7	35.1	294	76	128	185	113	0.1659
T_1F_1	16.7	22.8	21.2	16.6	38.7	346	101	171	211	162	0.1955
T_1F_{1-1}	17.0	23.2	21.4	17.9	43.0	390	102	167	254	189	0.1999
T_1F_2	17.6	23.7	22.1	17.3	44.5	394	107	187	260	199	0.2236
T_1F_{2-2}	17.7	25.1	22.9	18.7	47.1	458	131	211	310	228	0.2325
T_2F_0	18.9	23.3	21.7	17.0	25.2	221	102	174	150	111	0.2423
T_2F_1	20.4	25.3	23.7	19.1	30.0	286	126	220	203	188	0.3149
T_2F_{1-1}	21.7	26.2	24.5	19.4	32.1	320	142	245	228	217	0.3644
T_2F_2	22.1	26.8	25.3	19.7	35.7	339	139	242	237	234	0.3633
T_2F_{2-2}	23.3	27.2	25.9	20.2	35.9	348	149	265	261	257	0.4129